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Peculiarities of Steel–Babbitt Surface Interaction under Ultimate Friction in a Magnetic Field

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The method of saturation of the friction surface with the donor material in non-conductive solutions and oils is presented. The local influence of the magnetic field (MF) on the physical model of the friction mechanism (babbit coating Б83 (paramagnetic class) in oil М10Г2к on hardened steel 45 (ferromagnet)) according to the shaft–liner contact scheme is investigated. The magnetic susceptibility of М10Г2к oil before and after operation of the friction unit is determined, where the highest indicators of magnetic susceptibility of oil in the spent sample are noted. The influence of the action of the directed energy of the MF on the creation of a nanostructured coating on the ferromagnetic shaft (ст45) and the retention of the paramagnetic material of the babbitt liner is investigated. The magnetic-dynamic effect of the mechanism of 'prowling' by the products of wear of the insertion site on the friction surface of small wear particles in the intersurface working space 'steel shaft–insert Б83' is established. The effect of the mechanism of separation of paramagnetic material on the ferromagnetic surface during the formation of protective films on the friction surfaces is noted. The intensity of the coating under which the conditions of wear resistance of babbitt are maintained is determined. It is established that the intensity of wear under the influence of MF decreases by 1.5–2 times.

Key words: bearing, friction, magnetic field, nanostructure, wear products.

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Представлено методику насичення поверхні тертя матеріалом донора в електронепровідних розчинах і оливах. Досліджено локальний вплив магнетного поля (МП) на фізичну модель механізму тертя (баббітове покриття Б83 (парамагнетного класу) в оливі М10Г2к по загартованій сталі 45 (феромагнетику)) за схемою контакту вал–вкладень. Визначено магнетну сприйнятливість оливи М10Г2к до і після напрацювання вузла тертя, де відмічено найбільші показники магнетної сприйнятливості оливи у відпрацьованому зразку. Досліджено вплив дії направленої енергії МП на створення наноструктурного покриття на феромагнетний вал (ст45) та утримання парамагнетного матеріалу вкладиша з баббіту. Встановлено магнетно-динамічний ефект механізму «рискання» продуктами зносу місця впровадження на поверхню тертя дрібних часток зносу у міжповерхневому робочому просторі «сталевий вал–вкладень Б83». Відмічено дію механізму сепарації парамагнетного матеріалу на феромагнетну поверхню під час формування захисних плівок на поверхнях тертя. Визначено напруженість роботи покриття, за яких витримуються умови зносостійкості баббіту. Встановлено, що інтенсивності зношування під впливом МП зменшується в 1,5–2 рази.

Ключові слова: підшипник, тертя, магнетне поле, наноструктура, продукти зношування.

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1. INTRODUCTION

Conversion of gas turbine engines (GTE) for gas pumping is a fundamentally new direction with the requirements of extending the life of aircraft engines, up to 30–50 thousand hours, and sometimes up to 100 thousand hours of operation, the cost of which currently reaches a quarter of a billion UAH. However, about 20–25% of natural gas compression compressors lose their performance due to the failure of the babbitt bearing (liner) of the main support unit of the rotor, which works in a lubricating medium according to the friction scheme of the shaft–insert. Structural composition of the friction surface of the shaft there are alloys based on iron (ferromagnetic class) and paramagnetic elements of the babbitt coating.

The third element of the friction pair is the oil. Analysis of spent oils shows that their content is enriched with all the elements from which the parts of the target functional system (FS) are made, both in the molecular state and in the form of small particles that come into contact with the oil as it moves along the transmission. [1, 2]. The saturation of the components of wear actively comes from the most loaded contact points of friction pairs. Operational practice of technical means indicates that 70–80% of mechanisms fail due to wear of friction surfaces and reduction of bearing parameters of lubricating medium. Each of the elements characterizes the wear of a separate unit of the mechanism of the FS part, depending on their structural and elemental components, load and temperature effects.

The equivalent problem affects all working mechanisms that perform energy transfer or conversion. For internal combustion engines, mechanical impurities at a concentration of 0.1% in the oil significantly affect the wear of the contact surfaces. However, the amount of impurities ambiguously affects the wear and depends on the gap between the friction surfaces. In the article [3] it is noted that even large impurities can migrate in the space between the friction surfaces. Those larger than 15 microns are selected by filter elements (fine cleaning 10–15 microns), but all that is less returns back to the contact zone passing through the cycle of the lubrication cycle.

Oil purification of aircraft GTE in the process of refueling the lubrication system is controlled up to the range of 10–16 μm. The most important characteristic of the oil condition is the antifriction properties that are able to protect the working surfaces in conditions of ultimate and liquid friction.

The structural component of the babbitt surfacing on the inserts in the sliding bearings (SB) of the turbine shaft is tin (β-Sn) (Б83, Б89) with magnetic parameters of the paramagnetic class.

There are many ways to restore and keep a sliding bearing in working condition, from surfacing to electroerosive and laser technology. Each of them is more or less adjusted and improved. For example, an intermediate layer of copper helps to ensure the removal of temperature from the friction zone.

2. PROBLEM STATEMENT AND PURPOSE OF RESEARCH

The primary parameter characterizing the operating conditions of the tribosystem is the formation, during the friction process, of protective surface films capable of fulfilling the technical requirements of the designed mechanism. The leading helper in the formation of protective surfaces are donors of elements with characteristic properties and directed action of auxiliary energy flows towards the unstable surface structure of the friction surfaces of a details pair during mechanical movement. Donors must be subject to directional movement under the action of external energy flows in non-conductive lubricating media.

The aim of the work is to determine the influence of magnetic field (MF) on the tribocoupling 'babbitt coating–oil–steel' in the formation of surface structures at the macro and micro levels to study the parameters of SB tribo restoration in gas pumping units.

The basis of this technique of surface restoration is based on the mechanisms of application of nanocoatings from donor materials during operation. For this purpose it is necessary: 1) to formulate a model of wear of a shaft of the turbine in pair with an insert of the babbitt bearing; 2) to characterize the direction of MF and the power of magnetic fluxes through the contact zone at the time of friction; 3) determine the mechanical parameters and chemical composition of alloying elements on the friction surface.

Since wear particles have a wide range of both properties and composition (particle fraction, mechanical parameters and significant differences in magnetic susceptibility), this allows us to conclude that it is impossible to simultaneously sort and move the entire range of materials in the space of the contact zone. Therefore, it is necessary to emphasize the base material in the structure and the system of influence on them, which will simplify both the study of the interaction conditions of the elemental composition and the technology of testing the material control mechanism (wear products) in the surface contact volume during friction.

The disadvantages of the babbitt liner after melting include: transitions in the surfacing of non-continuous and porous coatings that are associated with overheating; penetration to the steel base with the formation of cracks, much slower etching, as evidenced by the presence of the intermetallic phase of FeSn, which increases the fragility of the working area.

Given that babbit SB (Б83) work due to the basic element of tin, according to the physical properties of the wear products, under the action of MF, will be concentrated in the zone of actual tribological contact, where is the highest density of magnetic lines (ML).

The research hypothesis is based on the control of wear and simultaneous renewal of friction surfaces by nanocoating during operation.

Even at a small MF intensity of 0.1–0.5 T, all magnets change their internal structure which in the crystal cell the mobility of point and linear defects increases [4].

An important factor of influencing at the parameters of the interaction of surfaces during relative displacement is the surface deformation and reduction of the hardness of wear products due to changes in the dislocation structure of the material under the action of magnetoplastic effect (MPE) [5]. Too little additional MF energy ($B \sim 0.2$–1 T) is able to detach the dislocations from the stoppers, displace the Burgers vector, reduce the strength and increase the deformation parameters of the crystals [5]. Deformation in MF of austenitic steel X18H9T and steel 3 leads to additional generation of acoustically emission signals. When testing samples in MF and without it, the main reason for the impact of MF on plastic deformation is not a change in the thermoactivation parameters of plastic flow, but a significant restructuring of dislocation ensembles involved in the deformation process [6].

The origin of the effect of the orientation of the crystalline layers of tin from the melt on the surface of polycrystalline samples in the MF from the centers of crystallization reproduces the directed structural macroscopic regions of the surface layers [7]. Studies have shown that in the molten and crystallized layers, the orientation throughout the volume is probable.

3. MATERIALS AND METHODS OF RESEARCH

The choice of research conditions of sliding bearings is carried out according to ГОСТ 16429-70 on types of friction: liquid, boundary and without greasing. As the lubricating medium in the contact zone decreases, the friction acquires transient mixed boundary lubrication, with the formation of boundary films, the thickness of which varies from 0.01 to 0.09 μm [8]. The bearing capacity of bearings, on the same type of long-term modes, at easy and average conditions, the *PV* parameter fluctuates about 715 MPa·m/s, for babbitt coverings on the basis of tin [9].

Babbitt inserts are always operated in oil, which in the process of operation is saturated with wear products (WP) of different fractions and elements of details. We studied the WP particles in М10Г2к oil during the formation of two surfaces as a result of friction. Their size and number (Fig. 1) on the surface plane are determined using a metallographic microscope, which shows that the fractional composition of the WP is quite wide, but dominated by particles with a value close to 2–10 μm.

The calculation of the magnetic susceptibility of the oil is performed according to the algorithm.

The frequency of oscillations in the circuit is equal to:

$$f = \frac{1}{2}\pi\sqrt{LC}.$$

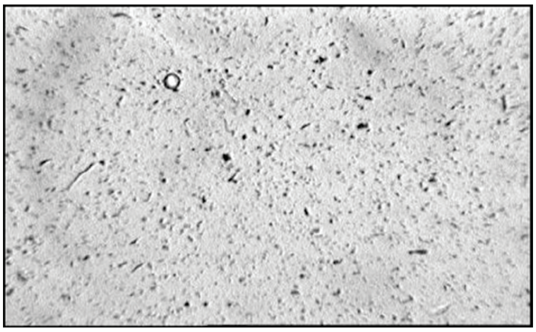


Fig. 1. Wear surface in the operated oil, quantitative and fractional composition of oil М10Г2к (×400).

Inductance of MF:

$$L = \mu_0 \mu_{oil} S_{loop} N_{loops}.$$

Hence the frequency of the empty coil is equal to:

$$f_0 = \frac{1}{2}\pi\sqrt{\mu_0 S_{loop} N_{loops} C},$$

where μ_0—magnetic permeability of vacuum, S_{loop}—loop area, N_{loops}—the number of turns in the coil.

The frequency of the circuit with the filled coil is calculated as:

$$F_{oil} = \frac{1}{2}\pi\sqrt{\mu_0 \mu_{oil} S_{loop} N_{loops} C},\ f_0^2 = f_{oil}^2 \mu_{oil},\ \chi = f_0^2 / f_s^2. \quad (1)$$

The influence of MF on changes in the structural parameters of magnets in the formation of the internal order of the material increases the deformation component by 10–15%. In this case, without deformation, the mechanical and plastic properties do not change, which indicates the dislocation mechanism of deformation parameters in the electro-plastic effect [9].

MF reduces the binding energy of dislocations and increases their mobility towards the surface during friction [10]. That is, the change in the energy state of the surface during friction affects the movement of linear defects of the crystal bed (dislocations) in the direction of decreasing entropy by directing towards a positive gradient to the surface with the formation of protective films. The analysis of admissible loadings of working sliding bearings (Table 1) allows drawing conclusions on substantiation the parameters of tribological process modelling.

The study of babbitt coatings is based on the energy ratio E/A, according to the publication [11], which indicates a virtually unchanged value of the allowable parameter for a certain range of load ratios and sliding speeds.

Thus, the basis for the creation of surface protective films (coatings) is the production of wear products during friction. Under conditions of

TABLE 1. Limit modes of operation of products from material Б83 ГОСТ 1320-74.

Mark of babbit	Load characteristics	Specific pressure p, kgf/sm^2	Circular speed v, m/s	The intensity of work PV, kgf/m sm^2 s	Operating temperature, °C	Using
Б83	Quiet	150	50	7500	70	Bearings operating at high speeds and medium loads
	Shock	100		500		

friction, the area of actual contact (AAC) perceives an increase in load from 10 to 10000 times compare to the load on the nominal area. If we take into account the maximum contact loads, the tangential area in the AAC will take about 40% of the nominal area [12]. From here, 60% of the space and volume above it is filled with oil and WP (Fig. 2).

WP that has its own internal unstable (excess) energy will interact with the loose structure of the surface layer and fill the 'energy wells' on the defects of the crystal structure. Experimental studies of the pair of shaft–liner are based on the force of resistance and are a function of a number of parameters related to the mode of operation and the environment in which the mechanism operates (Fig. 2).

Thus, the presented physical model controls the mechanism of tribocoupling of the contact zone and its influence on the initial parameters, the basis of which is wear.

Tribological studies of sliding bearings when lubricated with oils and under the influence of the directed action of the MF have several fields of similarity: kinematic—in speed and load for the two considered movements; at dynamic similarity systems of force fields of an electro-magnetic origin are realized; mechanical—copies geometric, kinematic and dynamic similarities; thermal processes are controlled by *PV* parameter.

Therefore, each of the similarities may be a specific field for achieving and defining a tribological model with mixed lubrication.

The physical model of contact is presented (Fig. 2): shaft is the ferromagnetic material, the insert is a babbitt coating (β-Sn paramagnetic base) applied to the ferromagnetic base. The recovery model is based on the influence of the directed action of MF on the WP, which are formed during friction from both surfaces.

At the moment of collision of surfaces the MPE is present in the point A at zones of AAC have the maximum mechanical deformation of

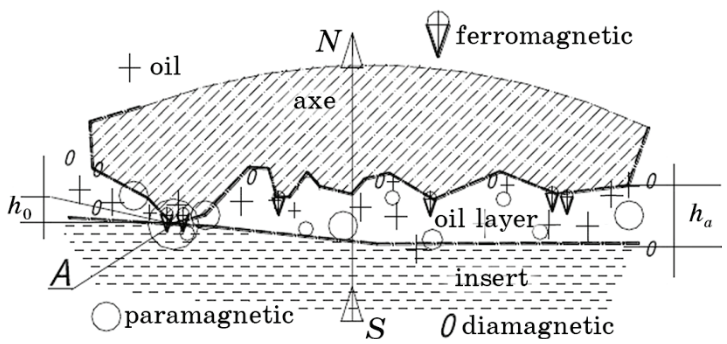


Fig. 2. Scheme of interaction of lubricating medium with nanoparticles of metals in the area of working contact of the tribological unit under the action of MF at point A.

materials of para- and ferro- magnetic classes. The moment of contact is characterized by temperatures much higher than the Curie materials, so at the time of contact the steel acquires paramagnetic properties, which equalizes the magnetic parameters of both materials (*i.e.* tin and steel) for some time. Under these conditions, the largest amount of ML is concentrated through the point, which significantly increases the magnetic induction B and draws ferro- and para-magnetic components of materials into the contact zone. In parallel with the saturation mechanism, the diamagnetic components of the materials will be removed from the areas around the contact by mixing with the oil filling the depressions in the rough topography of the surface.

At the points of contact, there is no physical distance between the surfaces, and the induction of MF between the poles is constant. According to Coulomb's law, the force of interaction of magnetic poles $F = k_{\text{magn}}(M_1M_2)/r^2$, where k_{magn}—magnetic constant, which depends on the choice of units of 'amount of magnetism', M_1 i M_2—the amount of magnetism at the poles, r—the distance between the poles (the thickness of the separate tribo film and the volume of oil between the surfaces during liquid lubrication). Thus, the force of interaction of magnetic poles F, which at the poles according to the experimental data is equal to the magnetic induction $B = 0.3$ T, due to surface roughness, the distance between surfaces decreases or increases, which affects the migration of ML at a particular time at these points of contact. Given that the AAC of friction surfaces is 0.1–0.0001 of the total working area, which in our case is equal to 1 cm^2, the magnetic induction of 0.3 T is compacted 100 times per area of 1 mm^2 and passes without resistance only in places of actual contact on freshly created planes, and can reach up to $B = 30$ T in the point state, moving over an area of 1 cm^2. That is, the magnetic flux through the AAC will be, at the points of contact of significant value, $F = (0.3 \cdot 10000/100) = 30$ Wb. According to A. V. Chichinadze the topography of each of the surfaces has upper points of location at a distance of 0.8 mm to 10 mm [13] from each other, which are on the bearing surface, and in a fraction of a second (contact time, at a relative displacement of 2 m/s, is $4 \cdot 10^{-4}$–$5 \cdot 10^{-3}$ s) change their position and shape of contact on the plane of friction. It is known that the speed of propagation of the MF reaches 300000 km/s, which allows it with a large margin of time to disappear and form elsewhere throughout the field of actual contact.

However, if the magnets are far enough apart and their axes are directed in one direction, the force with which one acts on the other can be described as $F = (3\mu m_1 m_2)/(2\pi r)$, where m_1 i m_2—magnetic moments. The equation shows that the strength of the interaction between the magnets decreases quite rapidly—in proportion to the third degree of the distance between them.

However, in the area of contact (more than 60%) between the existing irregularities of the rough surface in the volumes of the recesses is oil mixed with WP of different classes of magnetic parameters. When changing the mechanisms of friction and lubrication conditions, the action of the MF affects the sorting of the WP between the surfaces due to the energy costs of the field to move them. Hence, according to Coulomb's law, in the places of depressions, the distance ha (Fig. 2, h_a) the force of the MF will decrease significantly due to the distance between the contact surfaces in the cube to the distance between the poles (from literature [14]) in the fourth degree. At a distance of up to 5 μm (Fig. 2, h_a) the friction takes place according to the rules of liquid lubrication of the interaction of contact surfaces, and the magnetic induction is $B = 0.012$ T, which reduces the field strength by 25 times from the specified. This mechanism of moving the WP in the intersurface volume will find a place for diamagnetic particles that can be part of the friction surfaces.

Thus, the physical conditions of the tribological process, under the action of MF, due to the magnetic properties of each of the materials involved in the technology of restoration of surfaces and the parameters of the roughness of the friction surfaces.

4. RESULTS AND DISCUSSION

4.1. Used Materials

Experimental data are obtained on a friction machine СМЦ-2 according to the scheme shaft–insert. Operating parameters in the conditions of extreme or mixed lubrication for Б83 does not exceed the *PV* factor (750 MPa = 7500 kgf/sm^2 (Table 1)), therefore we choose research modes $P_{\max}$ (loading) = 7.5 MPa = 76.48 kgf/sm^2, $V_{\max}$ (speed) = 2 m/s, angular velocity of the shaft $n = 764$ min^{-1}, the roughness of the contacting surfaces: $R_{zj} = 1.6$ μm for shaft and $R_{zb} = 3{,}2$–$6{,}3$ μm for the bearing with a babbitt covering, contact area 1 sm^2. For the organization of the magnetic environment used neodymium magnets made according to ГОСТ 17809-72 at the size of 10×10×10 mm. The medium is М10Г2к motor oil, MF $B = 0.3$ T, directed perpendicular to the plane of friction from the coating to the center of the shaft, *i.e.* from the pole 'S' to the pole 'N' (S/N). The diameter of the pin $d = 50$ mm, the length of the bearing liner 10 mm. The path of friction of the liner is determined by the scheme, from the length of the sector of the circle $l_2 = 2\pi R = 0.157$ m. At a speed of 2 m/s the path in 1 km the insert will overcome in 8.33 min. Tribological wear parameters are recorded gravimetrically on ANG200C scales with an accuracy of 0.0001 g.

The ratio of MF to oil is characterized by an unbalanced magnetic moment of unpaired electrons, the spins of which compensate each other with certain frequency parameters of the system. The order of

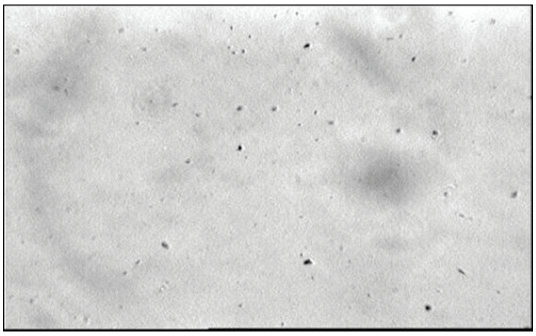


Fig. 3. Quantitative and fractional composition of the WP in the operated oil М10Г2к after friction under the action of MF (×400).

which affects the magnetic susceptibility of the material (environment), χ_M the content of impurities changes the susceptibility of the system. The study of oil samples on the fractional parameter of the WP after friction under the action of MF indicates a significant reduction in the number of fine particles (Fig. 3). As they are separated into a magnetic flux that is concentrated in the AAC sites, the software moves faster in the oil volume. From what the basic part of them is constantly, in a zone of normal contact and takes part in restoration of zones of AAC.

The results of oil replacement are investigated on the equipment developed at the Institute of Magnetism of the National Academy of Sciences of Ukraine which are presented in Table 2. It is seen that the magnetic susceptibility (MS) of the oil sample М10Г2к after friction without MF is $\chi = 2.94$ (Fig. 1.), due to the free movement of the WP in the volume of oil. Their presence is controlled only by the technological capacity of filter systems. In the oil sample after friction in the MF (Fig. 3) $\chi = 2.69$ smaller, as part of the WP, fixed in the mass of the lubricant MF and sent to the contact zone for magnetic-tribological deposition on the excited surface deformation.

The tribo-magnetic parameters of the operated oil calculated by algorithm (1) are presented in Table 2.

TABLE 2. Determination of magnetic susceptibility χ of oil.

	Contour core with filled coil F (М10Г2к), Hz	Average value χ (М10Г2к), 10^{-4}
Control sample of oil	13.36973	2.49
Sample oil after friction in MF	13.36946	2.69
Sample oil after friction without MF	13.36926	2.94

4.2. Analytical Substantiation of Results of Tribological Researches

The basis of tribological contact is the directed action of energy imbalance in the contact zone, so the directed effect of MF on the contact plane depends on the correct location (in this case) of permanent magnets relative to the friction zone. For this purpose, the ML fields are directed from the counter body (*i.e.*, the model shaft of the turbine) perpendicular to the friction zone of the babbitt insert deposited on a steel (ferromagnetic) base (Fig. 4).

The directed action of the force MF allows the wear products of the ferromagnetic class to be the first grouped on the surface in the direction of the field (Fig. 5), followed by paramagnetic tin particles formed during the wear of the babbitt insert.

With liquid lubrication, the working surfaces of the shaft and the insert are separated from each other by a layer of oil, the thickness h_a (Fig. 2) which must be greater than the sum of the heights R_{z1} i R_{z2} surface roughness (Fig. 5). Under such conditions, the babbitt coating absorbs the external load and prevents wear of the working surfaces of

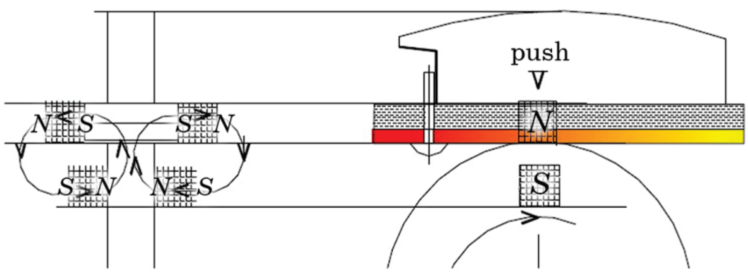


Fig. 4. The layout of the magnets for the directional action of the MF from the shaft to the babbitt through the zone of tribological contact during the application of ferro- and paramagnetic WP.

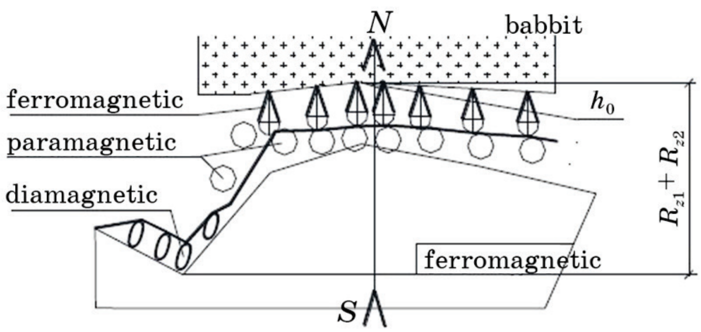


Fig. 5. Model of layer-by-layer arrangement of wear products between paramagnetic friction surfaces in the directional MF from the shaft on the SB.

the shaft and the insert, preventing their direct contact. In this case, the resistance to movement will provide only internal friction in the oil layer. The coefficient of friction at liquid greasing is insignificant (0.008–0.005), losses on friction and heat release in the bearing are the lowest.

However, not everything is so simple, the greatest wear is observed on the surfaces of antifriction materials with a semi-liquid or boundary nature of lubrication, the coefficient of friction increases to the level 0.008–0.01 [15].

Given the tribological parameter of the babbitt coating without the action of MF (Fig. 6, *a*), we observe wear at the level of 0.15 mg/km on the path of 12 km. When the path increases to 18 km, the wear decreases sharply, which can be explained by the formation of intermediate protective tribological films on the friction surface, which in stable conditions are sufficient for operational parameters. Under the action of MF, based on 12 km, wear is characterized by a significant reduction of almost half to 0.085 mg/km (Fig. 6, *b*) with increasing path gradually decreases wear, due to the formation of protective tribological films on the work surface with constant addition of oil from the total oil mass to the zone contact. In parallel on points of AAC there is a mechanical rubbing with the maintenance of particles of wear in MF. The results of wear are presented in Fig. 6, *b*, the coefficient of friction at a stable mode of friction (Fig. 6, *b* columns 5, 6, 7) is 0.08–0.05.

The structure of high-tin babbitt Б83 consists of two reinforcing phases: β-phase, these are SnSb crystals with a size of 100–200 μm with a hexagonal and rhombohedral lattice; η-phase in the form of large connection needles (Cu_6Sn_5), and β-Sn filler with paramagnetic properties.

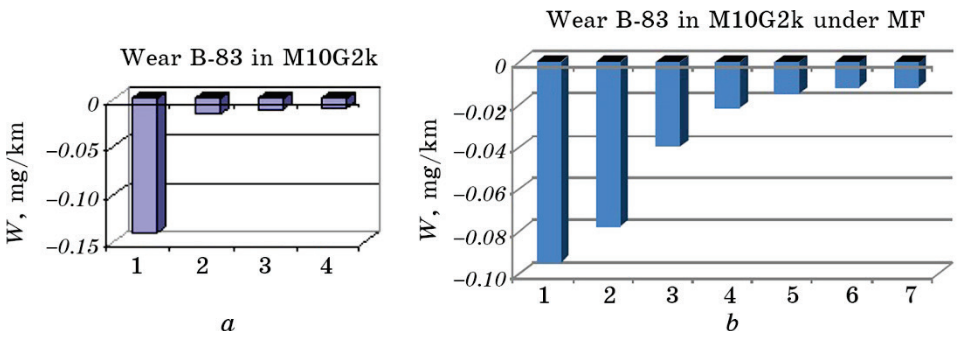


Fig. 6. Tribological parameters of Б83 according to Ст45 hardened to martensite in М10Г2к: 2—wear intensity without MF, 3—wear intensity in MF directed to the center of the shaft: 1—distance 12 km, 2—18 km, 3—30 km, 4—42 km (*a*), wear resistance of a babbitt covering under the influence of MF: 1—12 km, 2—18 km, 3—30 km, 4—42 km, 5—45 km, 6—50 km, 7—55 km (*b*).

Significant effect on magnets with a crystalline structure is the effect of MPE [16], according to which the plastic parameters of magnets of ferro- and paramagnetic classes of both wear products and friction surfaces increase. Based on the combined parameters of the deformation of the mechanical component and the flow of MPE contact zone forms a mixed coating of the elemental composition of the surface materials of both components of the friction pair. The layered structure of which is located from the ferromagnetic material to the paramagnetic on the outer layers of the surface depending on the magnetic susceptibility of the material.

MF in the AAC zone by increase the deformation of the metal by 4–8% [17], changes the ratio of stresses on the surface area of the weakly magnetic tin by rubbing it between the contact areas filling them, which significantly reduces the specific load on the contact.

At normal contact around the AAC zone, the wear products of the ferro- and paramagnetic class (Fig. 5) accumulate in the intercontact volume, the denser the greater their magnetic susceptibility.

Ferro- and paramagnetic structures are grouped into magnetic domains which at different states of the material are oriented parallel to the direction of the MF. This behaviour of the system characterizes the mechanism of accumulation of the donor for application to the friction surface, in the amount that wears out. The rest of the wear products is transported by oil to the filters and sludge.

The mechanism of construction of the surface layer at the points of AAC is based on the change of the parameters of the crystal bed of the ferromagnet during the transition through the Curie point. The initial layer is grouped from ferromagnetic WP (since they have a magnetic susceptibility of about $\chi_m = 700$, in iron-based alloys at 0.002 T and permeability $875 \cdot 10^{-6}$ N/A^2). The initial stage of movement of the components of the friction unit begins with tin (Curie point 30°C) above which acquires a diamagnetic state (magnetic susceptibility $\chi = +4.5 \cdot 10^{-6}$). According to the magnetic properties, it will move from the contact point and settle around the contact where the MF will be kept until cooling. Then mechanically move to the friction surface in the form of 'scales' (Fig. 7, *b*) And in the contact zone instantly acquire paramagnetic parameters (Fig. 5). In this case, it is logical to assume that the paramagnetic parameter of iron with b.c.c. bed will be much higher than tin (*i.e.*, the number $\mu_{Fe} > \mu_{Sn} = 1.00009$). When the contact temperature falls below the Curie temperature of iron, its crystal bed acquires a ferromagnetic state and is intensively formed at the points of AAC under the action of a significant MF. At temperatures below 30°C paramagnetic tin is shifted to a layer of metal coating.

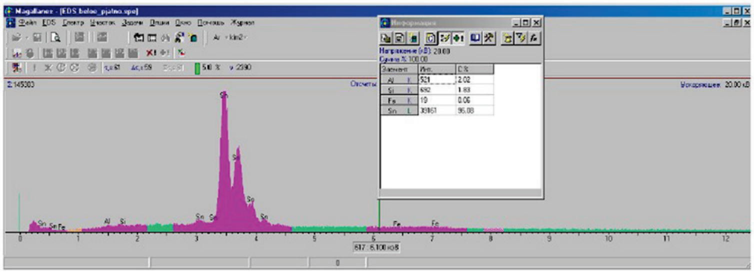
Subsequent interaction of the ferromagnetic shaft with the sliding bearing in the direction of the MF in the babbitt alloy (tin-based) interacts with the tin layer.

Therefore, when the MF is directed to the sliding bearing from the shaft, the ferromagnetic component will move to the coating and will be covered with a 'scaly' structure of tin.

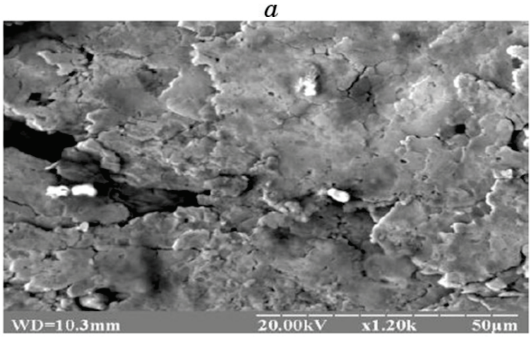
However in the mixed mode of friction all mechanisms of greasing which will correct force of resistance are possible.

Changing the direction of the MF from the insertion of the babbitt coating 'S' to the shaft pole 'N' (S/N), the WP of the ferromagnetic class remain on the shaft pressed MF with reduced strength under the action of the MPE. Meanwhile, the paramagnetic WP cover the surface by placing it on the shaft on top of the ferromagnetic layer according to the magnitude of the magnetic favorability (Fig. 2). Given the decrease in the hardness and strength of the WP particles, the movement of tin in the contact zone takes place on the coating of the ferromagnetic class in the plastic state of the diamagnetic phase at temperatures below 20°C. The basis of plasticization of macrohomogeneities (cracks, inclusions, microdefects, displacement of dislocations) is the concentration of mechanical stress and MPE which allow to reduce the level of residual stresses on the volume of material with a crystalline structure under the action of pulsed MF [18, 19].

Metallographic studies of the friction surfaces of steel 45 paired



a



b

Fig. 7. Formation of a tin coating on the steel surface in the direction of the MF according to Fig. 2: chemical analysis of surface formation (*a*), topography of tin layering on steel surface (*b*).

with a babbitt coating (Б83) in the medium of oil М10Г2к under the influence of MF indicate the accumulation and retention of tin on the friction surface (Fig. 7, *b*).

Tin conglomerates from Б83 wear products create a scaly film that covers the surface with a solid layer 1–4 μm thick. The movement of tin on the surface of steel 45 in the MF is directed in the opposite direction from the direction of friction. According to the obtained metallographic results of the surface layer, the location of the tin forms conglomerates stretched along the direction of the friction track forming surface films. Due to the low melting point of the friction unit, the tin film acts as a lubricant. The deformation change of tin during creep reaches $\varepsilon = 5\%$ [20] changing the ratio of dynamically fractional processes, creating structural surface films of conglomerate structure.

Thus, the surface of the shaft will have the structure of a 'sandwich' of steel and tin with impurities of other elements. Thus, the mechanism of the friction regime is characterized by the shear resistance of the tin surfaces in the oil at the level of AAC interacting on the protrusions of the roughness.

However, the mechanisms of interaction of MF on energy-unstable areas of crystalline materials are insufficiently studied, so they need fundamental research in this direction, taking into account the known mechanisms of friction and wear in tribology.

According to B. I. Kostetsky, the conditions of normal friction and wear in accordance with the structural-energy theory require compliance with several postulates:

1) Localization of plastic deformations, destruction of the internal structure of the upper layers in the secondary structures formed by friction. In our case, the plastic deformation in the AAC zone is increased by the action of MPE in paramagnetics.

2) In terms of B. I. Kostetsky, the dynamic equilibrium of mechanochemical processes of formation and destruction of secondary structures ensures the established course of the process, maintained and renewed by supplying oxygen from the outside. Given the paramagnetic properties of oxygen, which will be displaced in the space between the poles of the magnet, *i.e.* between the friction planes, the conditions for the formation of oxide tribological films are added.

The initial stage on the way of 12 km, the process of surface smoothing is characterized by almost twice less wear (Fig. 6, *b*) to $I = 0.085$ mg/km compared to wear without MF (Fig. 6, *a*) $I = 0.148$ mg/km. The running-in stage up to 42 km takes place with a gradual decrease in wear to the level of 0,008–0,005 mg/km. The reduction of wear (Fig. 6, *b*) of the Б83 coating under the action of MF is due to the stable amount of WP as donor materials at the points of AAC. Particles of ferromagnetic material from the shaft and paramagnetic tin saturate the contact zone due to their delay in the area of the positive gradient of paramagnetic materials relative to the MF. Where their number reaches a critical thickness of up to 2–3 microns is stabilized, due to the restructuring of the dislocation structure, which allows to soften the surface layers of the ferromagnetic and paramagnetic components of the materials used (steel and tin) below the Curie temperature. In addition, a significant effect on the content of these materials and their oxides (with sufficient oxygen (paramagnetic) and the minimum component of hydrogen (diamagnet)) in the contact zone, create in the field of action of MF at the points of AAC thin tribological films [19].

Simultaneous action of MF and mechanical load increases the course of dislocations that have the same symptoms as in separate action, but pass thousands of times faster [21].

The wear resistance of the SB shaft is explained by the change in the structural component of the ferrite-perlite steel and part of the ferrite α-Fe—ferromagnetic environment to austenitic γ-Fe (austenite—paramagnetic) in the surface layers under the action of MF with mechanical change of the deformation component. The structure acquires a layered composition, where the structure of α-Fe will house the austenitic component (γ-Fe) which has a higher hardness [22].

So a set of parameters: deformation component, WP application under the influence of MPE, MPE serves as an important characteristic of the creation of tribological films and balancing wear processes.

As noted earlier, the complex mechanical and magnetic action significantly increases the deformation and chemical components in the formation of tribological parameters of surface films. According to the data of [23], the volume of protective films decreases and their cover area increases in parallel.

Under these parameters, the following conditions are maintained at the contact of the conjugate tribological surface: constant volume of protective film of reduced thickness, changes in the mechanism of friction disturbs the energy balance of the parameters of the protective films, keeping paramagnetic protective films in the contact zone.

Thus, the multilayer friction surface is formed in the process of imbalance of perception of energy flows of MF on the structural components of the material.

The scientific novelty is to reveal the mechanism of friction of ferro- and paramagnetic pairs under the directed action of MF. The influence of MF on the structural hierarchy of nanocoatings on the surface of a ferromagnetic material with a two-layer structure, first a layer of a ferromagnetic component and then a layer of a paramagnet, is determined. The basis of structural transformations is the directed action of the MF on the mechanical deformation component and the mechanism of the MPE and the creation of tribological films of a thin servitural structure.

Practical significance. Conditions for reducing wear of friction surfaces, control and restoration of the tribological unit in the process of operation allows to increase the durability of the whole mechanism.

5. CONCLUSIONS

1. Using the calculation and experimental methods, the magnetic susceptibility of the oil medium is determined, which is equal to $\chi = 2.69 \cdot 10^{-4}$ after the formation of friction pair surfaces, which is almost 8.5% less than the susceptibility of the oil that worked without MF.
2. It is established that in the process of boundary lubrication, the magnetic flux density due to the total number of the actual contact area points, it can be more than $F = 30$ Wb at magnetic induction $B = 0.3$ T. At point contact, the effect of MF is significantly increased by moving the ML on the normal contact of the friction surface.
3. The analysis of the influence of the directed action of the MF on the sorting mechanism of the WP in the lubricating medium in which the surface layer is formed, which reduces wear by almost half. The paramagnetic component is formed on the friction surface in the form of scales with traces of shear on the surface.
4. Changing the energy state of the tribosystem, by conveying the force of the MF to the ferromagnetic surface of the detail (shaft) leads to the retention of nanoparticles of materials in the contact zone, which allows creating a significant gradient of change in the deformation component of friction surfaces.

Recommendations (practical). Methods of tribomagnetic surface treatment during operation allow obtaining multi-layer coatings on the working surfaces of details.

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