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Physical Interpretations of Internal Magnetic Field Influence on Processes in Tribocontact of Textured Dimple Surfaces

V.Ye. Marchuk[1], M.V. Kindrachuk[1,*], V.I. Mirnenko[2], R.G. Mnatsakanov[1], A.O. Kornienko[1], O.V. Bashta[1], S.V. Fedorchuk[1]

[1] *National Aviation University, 1, Kosmonavt Komarov Prosp., 03058 Kyiv, Ukraine*
[2] *The National Defense University of Ukraine named after Ivan Cherniakhovskyi, Povitroflotsky Avenue, 03049 Kyiv, Ukraine*

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The physical interpretations of internal magnetic field influence on the processes and phenomena in places of tribocontacts with textured dimple surfaces were formed. Experimental studies have established that, along with traditional processes of formation and destruction of surface layer in tribocontact, there are processes of excitation of internal magnetic fields at edges of discrete regions. Depending on contact pair, induction of magnetic field at the edges of discrete regions is 44-65 mT. The physical processes of magnetic field influence on mechanism of wear products removal under conditions of boundary lubrication are considered. It is shown that the ponderomotive force in magnetic field is the force acting on a particle in nonuniform magnetic field and directs it towards a greater magnetic field induction – the edges of discrete regions. The physical processes of the internal magnetic field influence on lubricant are investigated. The internal magnetic field causes dipole-orientation polarization of lubricant molecules that absorb energy of the magnetic field. As a result, the number of diamagnetic molecules of lubricant increases, a stable lubricant layer on tribocontact surface is formed, and less energy is required to be spent on regeneration of boundary lubricant films, which positively affects wear resistance of surface layer of elements made with textured dimple surfaces. These processes retain their activity in process of friction when lubricant molecules move behind the magnetic field created by discrete regions edges. The dependence of lubricant loss tangent on temperature and magnetic field is investigated. Growth of lubricant temperature above 200 °C leads to a rapid increase in loss tangent by 1.8 times, in comparison with dielectric losses of lubricant not exposed to magnetic field, due to the formation of ion radical complexes and charge transfer systems, which contributes increase of relaxation losses by increasing number of dipole molecules and weakly bound ions.

Keywords: Internal magnetic field, Textured dimple surface, Lubricant, Discrete region, Induction of magnetic field.

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1. INTRODUCTION

Friction units for machines and mechanisms working without greasing use solid graphite lubrication, laminated materials such as MoS_2, Ti_3SiC_2 and composite materials reinforced with carbon nanotubes [1-3]. However, the advantages of solid lubricants completely disappear if the contact surfaces are non-ideal, for example, have steps, wavelengths and other defects in which the two surfaces are pitting.

One of the promising solutions that can solve the problems of reliability and durability of friction units and mechanisms in extreme conditions of operation, as well as create necessary conditions for lubrication with boundary friction is the use of discrete surfaces [4-7]. The mechanism of wearing discrete surfaces in conditions of boundary friction is complex and depends on many factors, and today little has been investigated [8]. Processes of friction and wear on surfaces with discrete regions occur on actual plane of contact between discrete regions. The main role of discrete regions on surface is to supply lubricant to contact area in order to restore lubricating action of boundary lubricant film after its destruction [9]. Rate of restoration of boundary lubricant film depends on the mechanism of supplying lubricant to places of tribocontact, diffusion, surface lubrication and spreading of liquid lubricant.

2. STATE OF THE PROBLEM

The complexity of processes and phenomena that occur in thin surface layers of tribocoupling, along with the traditional processes of formation and destruction of secondary structures, are accompanied by processes of excitation of electric and magnetic fields. Under certain conditions, the effect of magnetic field can greatly change the friction characteristics. These factors play an important role in the processes of friction and wear of machines and mechanisms [10, 11].

There are many publications devoted to study of the influence of external electromagnetic radiation on lubricants and processes of friction and wear. Electromagnetic radiation affects adsorption and diffusion processes, accelerating or slowing down them. The results of this influence are change in oxidation rate of contact surfaces, which leads to a change in the intensity of processes development of seizing, reducing wear, reducing temperature of oil and samples [12-15].

Physical interpretation of excitation of internal electric and magnetic fields in places of tribocontact today is the least investigated. Taking this into account will allow to logically organize complex research processes on the common methodological basis of system approach, which is based on known principles of purposefulness, modeling, physics, defining the basic pro-

*nau12@ukr.net

cedures for conducting systematic studies. This is especially important for development of theoretical foundations of tribology, because it allows combining various scientific and technical directions and disciplines.

The purpose of the work is to investigate the physical phenomena of the internal magnetic field influence on the processes of wear products removing in places of tribocontact with textured dimple surfaces.

3. MATERIALS AND METHODS

Investigations of magnetic field induction were carried out using teslameter EM4305/1 (accuracy class 2.5). The influence of permanent magnetic field on dielectric constant ε and loss tangent $tg\delta$ of lubricant was investigated using a three-electrode capacitive converter in the temperature range 293-423 K with a sample heating rate of two degrees per minute. The choice of ε and $tg\delta$ for researches is due to their high sensitivity, which far exceeds well-known properties such as density, viscosity, refractive index, etc., which are widely used in physical-chemical analysis. Measurements of ε and $tg\delta$ were carried out by an automatic bridge of an alternating current E8-4. The error of measurement of capacitance C was $\Delta C = 0.001C + 0.02$ pF and $tg\delta = \pm (0.02 \text{tg}\delta + 5 \cdot 10^{-4})$.

Investigation of tribotechnical characteristics of discrete surfaces in conditions of boundary friction was carried out in accordance with GOST 26614-85, which establishes a method for investigating materials in friction with limited supply of lubricant material. As sample material, steel 45 was used. Discrete regions (dimples) were formed on the working surface of a counterface made of 30KhGSA steel, by plastic deformation of material with dynamic action of the indenter using a special device [16] with parameters of the textured dimple surface: distance between rows of dimples $2.0 \cdot 10^{-3}$ m, distance between dimples in the row $2.0 \cdot 10^{-3}$ m, depth of dimple $1.5 \cdot 10^{-3}$ m. Additionally, textured dimple surfaces were strengthened by the method of ion-plasma thermocyclic nitriding [17].

For testing of discrete surfaces in conditions of boundary friction a friction machine M-22M was used. Contact of friction pair occurred under the "disk-block" scheme. As a lubricant, industrial lubricant I-20 was used in accordance with GOST 20799-75. To provide a mode of boundary friction, the lubricating device was used in accordance with the recommendations of GOST 26614-85.

4. RESEARCH RESULTS AND THEIR DISCUSSION

High wear resistance of textured dimple surfaces and particular discrete regions is due to the high protective effect of surface layers, as well as the high efficiency of boundary lubricant films. Lubricants, which are used to restore the boundary lubricant film destroyed in tribocontact, will be stored in discrete regions. The surface of the immovable sample 1 will be permanently lubricated by the flow of lubricant material 6 (Fig. 1) stored in discrete regions under the action of the resultant force R, which pulls fluid particles to the rear edge 4, thus ensuring the regeneration of boundary lubricating film on surface of tribocontact. The resultant force R consists of forces of surface tension F_t and centrifugal (inertial) force F_i.

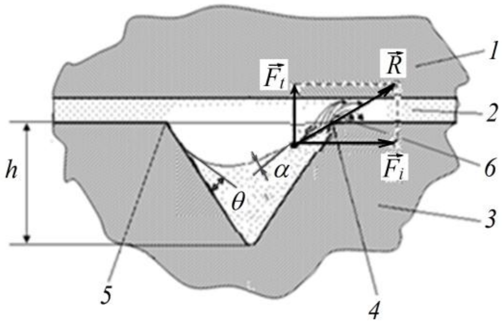

Fig. 1 – Movement of lubricant under the action of forces on it in the process of boundary friction: 1 – sample; 2 – lubricant; 3 – counterface; 4 – rear edge; 5 – leading edge; 6 – flow of lubricant

Along with the sufficient oil content of discrete regions, the active resultant force will provide a high rate of lubricant flow on regions of actual tribocontact in inter-dimple space, accelerating the process of regeneration of boundary lubricating film, which is determined by time of adsorption filling of gaps in its regions. These processes improve the tribotechnical characteristics of friction and reduce the wear of contacting surfaces.

Magnetic properties of the textured dimple surfaces affect processes of friction and wear by the formation of a mechanism for wear products removing. Experimental studies have established that on the edges of discrete regions an actual magnetic field is formed (Table 1). Depending on the contact pair, the induction of the magnetic field increases sharply and is 10-26 % higher, in comparison with the induction of the magnetic field between the dimples space, which is 44-65 mT. In a discrete region, the magnitude of the magnetic field induction drops sharply to 13-17 mT.

Table 1 – Influence of the contacting pair materials on the magnetic field induction on the contact surface of samples with discrete regions

Contacting pair materials	Magnetic field inductance, mT		
	inter-dimple space	dimple edge	dimple middle
Cast iron-cast iron	48	65	13
steel 45- steel 45	46	53	13
14Kh17N2-14Kh17N2	45	58	14
30KhGSA-30KhGSA	45	58	15
30KhGSA – steel 45	45	50	14.5
30KhGSA – steel 30	38	48	17
Cast iron – steel 30	40	44	17

The regularities of magnetic field influence on the mechanism of wear products removal in the conditions of boundary lubrication are established. As a result of force interaction between the magnetic field of wear products and the magnetic field of the discrete region edges, which far exceeds the magnetic field of the wear products and roughness of the friction surface, a non-uniform resultant field forms leading to the ponderomotive force arising F_P. The force F_P acts on wear particles and directs them in the direction of greater induction of magnetic field – the edges of discrete regions (Fig. 3a). Consequently, the ponderomotive force in a magnetic field is the force acting on a particle formed in the process of friction in a non-uniform magnetic field. It will be directly proportional to the half-square of the equipotential magnetic field of the equal potential of the edges:

$$F_P = m\chi \frac{H_e^2}{2},$$

where m is the mass of wear particles, H_e is the magnetic field of the edges of discrete regions, χ is the magnetic susceptibility of a wear particles.

Each particle of wear products in a magnetic field will be directed to the top of edge with a larger axis (Fig. 2b), which has a higher magnetization. Most of the particles will be concentrated near the leading edge in accordance with the direction of counterface rotation. This is due to the action of resultant force R on the lubricant flow 4, which limits the concentration of wear products at the rear edge, moving part of them to the leading edge and into the middle of discrete regions. This results in a greater wear on the vertex of leading edge, compared to the rear edge.

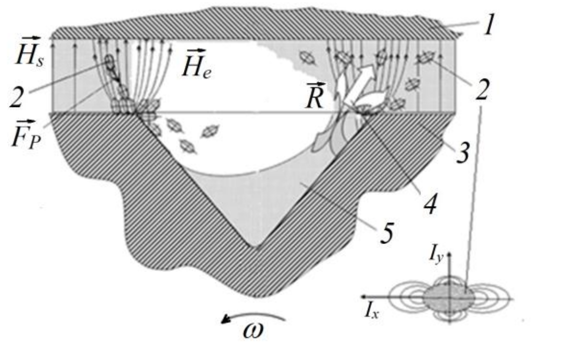

Fig. 2 – Physical model of a magnetic field influence on the mechanism of wear products removal in the dimple in conditions of boundary lubrication: *a* – dimple; *b* – a separate particle of wear products; *1* – sample; *2* – a particle of wear products; *3* – counterface; *4* – flow of lubricant under the action of the resultant force; *5* – lubricant; I_x, I_y – horizontal and vertical components of magnetization; H_e – equipotential fields of equal potential of the dimple edge; H_s – equipotential fields of equal potential of inter-dimple space

When wearing out the edges of discrete regions, the magnetic field lines are reduced to the magnitude of magnetic field induction of the inter-dimple space and the wear products are subsequently moved into discrete regions due to the inertial force. These processes eliminate the probability of occurrence of critical loads and temperatures in the friction zone and prevent the occurrence of inadmissible processes of the surface layer damage of inter-dimple space at the points of actual contact, which in aggregate improves the tribotechnical characteristics of the friction pairs and increases the resource of the entire tribosystem.

In addition, the magnetic field created by the edges also affects the lubricant, which results in a dipole-orientation polarization of the lubricant molecules within the boundaries of influence $\overrightarrow{B_e}$ by absorbing the energy of the magnetic field by the molecules of the lubricant. Since the lubricant is a diamagnetic, in the electron shells of molecule atoms (due to the phenomenon of electromagnetic induction) induction currents arise. The induction magnetic moment created by these currents, in accordance with the Lenz rule, is directed opposite to the magnetic field of the edges $\overrightarrow{B_e}$. The magnetic field induction of the lubricant molecules $\overrightarrow{B_{lm}}$ created by these currents will weaken the magnetic field $\overrightarrow{B_e}$ (Fig. 3). Therefore, the total magnetic field in the volume of the lubricant is characterized by a vector of magnetic induction and will be equal to

$$\overrightarrow{B} = \overrightarrow{B_e} - \overrightarrow{B_{lm}} = \mu_0 \overrightarrow{H_e} - \mu_0 \overrightarrow{J} ,$$

where μ_0 is the magnetic constant, $\overrightarrow{B_e}$ is the induction of the magnetic field of the discrete regions edges, $\overrightarrow{B_{lm}}$ is the induction of the magnetic field of lubricant molecules, $\overrightarrow{J}$ is the magnetization vector of the lubricant molecules. Given that $\overrightarrow{J} = \overrightarrow{H_e}\chi$, induction can be related to the intensity

$$\overrightarrow{B} = \mu\mu_0 \overrightarrow{H_e} = \mu_0 \overrightarrow{H_e}(1-\chi),$$

where $\mu = 1 - \chi$ is the magnetic permeability of the lubricant molecules, which shows how many times the induction of the magnetic field in the lubricant differs from the induction of the same field at the edges of the discrete regions.

The lubricant molecules retain the energy of their magnetic field in the event they are outside the magnetic field $\overrightarrow{B_e}$ in the process of friction. As known, the period of energy relaxation of hydrogen proton, after removal of magnetic field, is about 10^3-10^4 seconds, and of the electron is a hundredth of a second (the energy is given to lattice). Due to the superfine interaction, proton transmits the energy to the electron, the speed of its rotation around the hydrogen atom increases, increasing the induction of the magnetic field. This leads to the fact that the processes of the boundary film regeneration in the inter-dimple space will occur at lower energy costs.

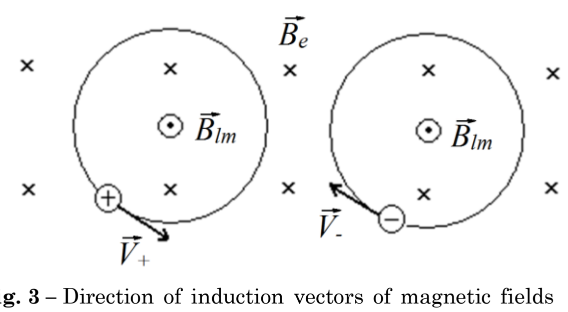

Fig. 3 – Direction of induction vectors of magnetic fields $\overrightarrow{B_e}$ and $\overrightarrow{B_{lm}}$

To confirm this conclusion, studies of the influence of temperature and magnetic field on the loss tangent were carried out (Fig. 4).

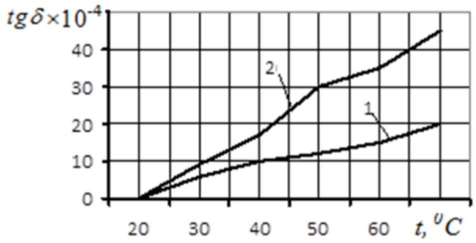

Fig. 4 – Dependence of the lubricant loss tangent on temperature and magnetic field: 1 – *tgδ*; 2 – *tgδ* after the magnetic field action

After the action of the magnetic field, dielectric losses (Fig. 4, curve 2) at room temperature remain practically unchanged. Further growth of the lubricant temperature leads to a rapid increase in the loss tangent by 1.8 times, in comparison with the dielectric losses of the lubricant not exposed to the magnetic field action (Fig. 4, curve 1). This is due to the formation of ion radical complexes and complexes with transfer of charge, which contributes to the increase of relaxation losses due to the increase in the number of dipole molecules and weakly bound ions. It can be explained by the fact that when the temperature increases, the lubricant molecules acquire thermal energy (W_m) and get the opportunity to orientate in the magnetic field created by the discrete regions edges (W_e) due to the fact that $W_e > W_m$.

Thus, under the action of the magnetic field on the lubricant, which is created by the discrete regions edges, the dipole-orientation polarization of the lubricant molecules takes place due to the fact that $W_e > W_m$. As a result, the number of diamagnetic molecules of lubricant increases, a stable lubricant layer on tribocontact surface is formed, and less energy is required to be spent on regeneration of the boundary lubricant films, which positively affects the wear resistance of the surface layer of elements made with textured dimple surfaces. It should be noted that the above-mentioned processes retain their activity in the process of friction when the lubricant molecules move behind the magnetic field created by the discrete regions edges.

5. CONCLUSIONS

Systematic notions about the laws and processes of the magnetic field influence on the mechanism of the wear products removal, which, in contrast to the existing, take into account the magnetic field of the discrete regions edges, are formed. It has been established and experimentally confirmed that the effect of attracting wear products to discrete regions of the textured dimple surfaces is the result of an increase by 10-26 % of the magnetic field intensity of the discrete regions edges in comparison with the magnetic field intensity in the inter-dimple space.

It was established that as a result of the interaction between the magnetic field of wear products and the magnetic field of the discrete regions edges, which far exceeds the magnetic field of the wear products and roughness of the friction surface, a non-uniform resultant field forms leading to the ponderomotive force arising. The force acts on a particle and directs it towards higher magnetic field intensity of the discrete region edge. So, the ponderomotive force in a magnetic field is a force that acts on wear products, forcing them to concentrate more on the leading edges, compared to back edges. This is due to the effect of the resultant force, consisting of the surface tension force and the centrifugal (inertial) force, on the flow of lubricant, which limits the concentration of wear products at the back edges of discrete region, moving part of them to the leading edges and in the middle of the discrete region. As a result, higher wear characterizes the apex of the leading edges of discrete region, compared with the back edges. This is confirmed by the data obtained as a result of experimental studies of discrete surfaces in conditions of boundary lubrication. Along with the sufficient oil content of discrete regions, the active resultant force provides a high rate of oil spreading on the areas of the actual tribocontact in the inter-dimple space, accelerating the process of boundary lubricant film regeneration. These processes improve the friction characteristics and reduce the wear of contacting surfaces.

It is proved that in the tribocontact with textured dimple surfaces the regeneration of boundary lubricating films consumes less energy due to the increase in the number of diamagnetic molecules of lubricating material, which is confirmed by the growth of the loss tangent by 1.8 times.

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Фізичні уявлення впливу внутрішнього магнітного поля на процеси в трибоконтакті текстурованих лункових поверхонь

В.Є. Марчук[1], М.В. Кіндрачук[1], В.І. Мірненко[2], Р.Г. Мнацаканов[1], А.О. Корнієнко[1], О.В. Башта[1], С.В. Федорчук[1]

[1] Національний авіаційний університет, просп. Космонавта Комарова, 1, 03058, Київ, Україна
[2] Національний університет оборони України імені Івана Черняховського, Повітрофлотський проспект, 28, 03049, Київ, Україна

Були сформовані фізичні уявлення впливу внутрішнього магнітного поля на процеси і явища в місцях трибоконтакту з текстурованими лунками. Експериментальними дослідженнями встановлено, що поряд з традиційними процесами утворення і руйнування поверхневого шару трибоконтакту, виникають процеси збудження внутрішніх магнітних полів на кромках дискретних ділянок. В залежності від контактної пари, індукція магнітного поля на кромках дискретних ділянок становить 44-65 мТл. Розглянуто фізичні процеси впливу магнітного поля на механізм вилучення продуктів зношування в умовах граничного змащення. Показано, що пондеромоторна сила в магнітному полі являє собою силу, яка діє на частинку в неоднорідному магнітному полі і спрямовує її в бік більшої індукції магнітного поля – кромок дискретних ділянок. Досліджено фізичні процеси впливу внутрішнього магнітного поля на мастильний матеріал, в результаті якого відбувається дипольно-орієнтаційна поляризація молекул мастильного матеріалу за рахунок поглинання енергії магнітного поля молекулами мастильного матеріалу. В результаті збільшується кількість діамагнітних молекул мастильного матеріалу на поверхні трибоконтакту, утворюється стабільний мастильний шар і менше енергії необхідно витратити на регенерацію граничних мастильних плівок, що позитивно впливає на зносостійкість поверхневого шару деталей з текстурованими лунковими поверхнями. Дані процеси зберігають свою активність у процесі тертя при виході молекул мастильного матеріалу за межі дії магнітного поля, створеного кромками дискретних ділянок. Досліджено залежність тангенса кута діелектричних втрат мастильного матеріалу від температури і магнітного поля. Зростання температури мастильного матеріалу вище 20 °С призводить до швидкого збільшення тангенса кута діелектричних втрат в 1.8 рази у порівнянні з діелектричними втратами мастильного матеріалу, не підданого впливу магнітного поля, за рахунок формуванням іон-радикальних комплексів і комплексів з переносом заряду, що сприяє збільшенню релаксаційних втрат за рахунок збільшення числа дипольних молекул і слабо зв'язаних іонів.

Ключові слова: Внутрішнє магнітне поле, Текстурована лункова поверхня, Мастильний матеріал, Дискретна ділянка, Індукція магнітного поля.