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Justification of the effect of the regularities of the flow of nanotribological processes in the materials of joint parts on the increase of wear resistance, reliability and efficiency of the functioning of machines and mechanisms

V.V. Aulin*, A.A. Tykhyi, O.V. Kuzyk, S.V. Lysenko, A.V. Hrynkiv, I.V. Zhylova, O.M. Livitskyi

Central Ukrainian National Technical University, Ukraine
E-mail: AulinVV@gmail.com

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Abstract

The article elucidates the essence of nanotribological processes in the materials of conjugation of samples of parts by the methods of the surface force apparatus, scanning tunneling and atomic force microscopy. The substantiation of the mechanisms of their occurrence is given by the methods of molecular dynamics and classical contact mechanics. Attention is paid to dry adhesive and contactless dynamic friction of conjugated samples, physical processes in "sticking-sliding" tribocontacts, adhesive effects, etc. The values of the lateral and normal forces acting on the probe were analyzed. The probe was considered as a collection of point particles of concentrated mass with a multiatomic structure of the material. The contact and movement of the probe with the surface of the sample was considered in the "probe-surface" system with minimal potential energy and lateral load and taking into account conservative and dissipative forces.

The effect of "sticking-sliding" is substantiated with the help of the apparatus of surface forces. The atomic periodicity of the effect is explained on the basis of the model of the formation and breaking of adhesive bonds and the "atom-magnet" model. It is shown that the patterns of "sticking-sliding" processes can be determined by using the parameters of shear stress and specific work of adhesion.

It is advisable to use the Johnson-Kendall-Roberts theory to explain the elastic adhesive contacts, and the Deryagin-Mullier-Toporov theory for the residual friction force and probe separation force.

It is shown that there is a significant connection between friction and adhesion processes. The correlation between the macroscopic value of the surface energy of materials and their shear modulus for homogeneous contacts was determined.

On the basis of adhesive effects and the effect of "sticking-sliding", it is possible to control frictional forces and create favorable conditions for their absence, which gives grounds for obtaining high wear resistance of tribo-joints of parts, their reliability and maximum efficiency of the functioning of machines and mechanisms.

Key words: adhesive effects, sticking-sliding, conjugated surfaces, lateral forces, friction, wear resistance, reliability, efficiency.

Introduction

The study of the physical nature of the processes of friction and wear at the atomic level of the materials of the joint parts became possible after the creation of atomic force microscopes. The intensive development of this technique led to the formation of nanotribology, which combined experimental and theoretical studies of adhesion, friction, wear, lubrication, chemical activity and triboelectromagnetism at the nanostructural level. As a rule, the problems associated with friction are mostly engineering in nature and are considered physics with macroscopic contacts of mating surfaces of parts contaminated by the presence of adsorbed particles, wear products, and lubricants [1].

The stimulus for the development of nanotribology is considered to be a fundamental understanding of the role of a set of microcontacts that occur when the surfaces of tribocoupled parts are in contact. At the same time, the total area of actual contacts may be significantly less than theoretical estimates [2].

Level approach in tribology [1-3] shows that the phenomena and processes in the contact area of tribojunctions of samples and parts are studied at the macro-, meso-, micro- and nano-levels. With the transition to a qualitatively new nanolevel of research, it was found that the physical processes in tribocontacts are much richer and more diverse and include many new phenomena: phase transitions due to the shear arrangement of thin films in the "probe-part surface" contact; the formation of contact "jumpers"; chemical, electrochemical and triboelectric effects; effects related to humidity, superconductivity, etc.

Literature review

An important place in the study of nanotriboeffects is occupied by questions that are considered using the methods of the surface forces apparatus and the quartz crystal microbalance technique. These methods are currently the most promising for nanotribology. To them can be added methods of surface nanoindentation technique, methods of scanning tunneling microscopy and atomic force microscopy [4-7].

The study of friction processes at the nanostructural level is of considerable interest for a wide range of technical applications: the technology of production and surface coating of hard magnetic disks for computers; production of microsensor sensors, etc. Engineering applications of tribology and tribotechnics in mechanical engineering require a deeper understanding of the tribological properties and characteristics of materials at the atomic level in order to optimize and predict the tribotechnical characteristics of joint parts. The successful solution of these tasks requires the reduction of the existing gap between the macro-, meso-, micro- and nanostructural levels of research on the materials of tribojunctions of samples and details of machines and mechanisms.

Adequate theoretical description of many experimentally detected tribophysical effects continues to be unsatisfactory, despite the fact that recently a number of important results were recorded, which were predicted and interpreted using the method of molecular dynamics and classical contact mechanics [8,9]. The mode of dry friction at the macroscopic level does not depend on the visible contact area and practically does not depend on the sliding speed. At that time, it is caused by a complex variety of surface properties, the presence of numerous microcontact zones, adhesive and deformation effects, as well as "ploughing" of the surface with microroughnesses and wear products [10,11]. To understand the nature of the most complex and least studied mechanism of adhesive friction, it is advisable to use a level approach in tribology.

One of the sub-levels of the nano-level is related to the need to build a detailed atomistic theory of triboprocesses, which describes the processes of adhesion, friction and wear within the framework of atomistic models of chemical bonding and elementary electron-phonon processes, which lead to energy dissipation in the surface layers of tribocoupled materials of samples and details [12].

Another sublevel of the nanolevel concerns the nature of the sliding mechanism, in which it is not clear whether the relative movement of the touching surfaces is continuous or consists of a series of discrete acts of sticking and sliding processes. The implementation of the latter processes requires the detection of the scale of distances and the time interval corresponding to elementary microslip. Experimental studies indicate that the sticking-slip processes are characterized by the periodicity of the material lattice, allowing to obtain the atomic contrast of the surface in the lateral contact mode of atomic force microscopy [1 3,14]. Note that this is possible only in the case of atomically smooth surface conjugations. Much more often, the contact area is contaminated by the presence of adsorbed substances and wear products.

The analysis of experimental and theoretical results obtained in the field of nanotribology in recent years is highlighted in the works of the following foreign authors [11-14]. It can be seen that an attempt is being made to construct some integral physical picture that is specific to nanotribocontacts as elementary friction zones. It should be noted that the results presented in the literature review were practically not discussed, and attempts to systematize theoretical ideas are fragmentary due to the fact that the main calculation models are in the stage of development and evaluation. Nanotribological adhesion-sliding processes based on models of adhesive friction forces and dynamic mechanisms of non-contact friction also require substantiation.

During the discussion of theoretical models of the tribon nanolevel in works [15, 16], much attention is paid to the problem of dry adhesive and contactless dynamic friction in a vacuum. At the same time, elementary processes are in the field of attention, the understanding of which brings researchers closer to the understanding of the nature of friction as a whole. Theoretical justifications of the effect of "plowing", wet friction, thermodynamic aspects of nanotribology and a number of other issues that require special consideration are considered in detail in literary sources.

This is a brief description of the main modes of operation of atomic force microscopy and other methods used in experimental research of micro- and nanocontacts [17,18]. Physical processes in tribocontacts, such as "sticking-sliding", adhesive, chemical and others, are discussed on the basis of available experimental material. At the same time, the existing theoretical concepts that allow the interpretation of these experimental data are considered.

The approximation of classical contact mechanics in the interpretation of atomic force microscopy data on "dry" adhesive friction in a vacuum is discussed. Simple models of the lateral movement of the probe are considered, which allow the interpretation of experimental images of the investigated surfaces of samples and parts. A detailed analysis of the evolution of the nanocontact structure using the molecular dynamics method is carried out. The mechanisms of static and dynamic friction are considered, the application of theoretical models is analyzed to explain the experimental dependence of the friction force on the load force, adhesion-sliding processes, interpretation of the damping effect of the motion of adsorbed films in experimental studies with a quartz microbalance [19,20].

The interaction of the tribodiagnostics probe and the surfaces of samples and parts allows not only to diagnose the structure of the contact zone on an atomic scale, but also to modify some properties of the conjugated surfaces.

It was revealed [21,22], to reduce the time of contact scanning of the technological process, it is necessary to increase the scanning speed to 1 cm/s It is noted that scanning probe microscopy, nanotribology and nanotechnology can lead to significant changes in mechanical engineering.

Purpose

The purpose of this work is to find out the influence of nanotribological processes occurring in the materials of conjugated samples of parts on their wear resistance, reliability and efficiency of the functioning of machines and mechanisms.

Results

Investigating the physical processes in the nanotribocontacts of the conjugated surfaces of the sample parts, we will focus on the theoretical justification of various experimentally observed phenomena. Among which the "sticking-sliding" effect is the key effect for the contact mode of atomic force microscopy. For the first time, the effect was observed at the atomic level when measuring the lateral forces acting on a tungsten probe sliding over the surface of highly oriented pyrolytic graphite. Similar measurements were carried out on a wide range of contacting materials from soft to hard.

Comparative studies of the "sticking-sliding" effect were conducted under the leadership of Fujisawa [2,3] for various combinations of probe and sample materials. At the same time, the observed periodicity of the sliding of the probe on the surface of the sample corresponded to the topography of the atomic relief of the surface itself, obtained in the normal mode of atomic force microscopy. At the same time, the positions of the maxima of the lateral and normal forces were slightly shifted relative to each other. The observed periodicity of the lateral interaction is believed to be responsible for all the observed contrast, including topographic images in the normal mode. The effect of "sticking-sliding" is revealed in experimental studies with the apparatus of surface forces [11,12]. The transition to continuous sliding without wear is observed at significantly higher speeds. At the same time, the question of the effect of the observed "sticking-sliding" periodicity on the fact that the atoms of the probe relax into a structure comparable to the atoms of the sample should be clarified. It was found that even for probes with a disordered atomic structure, periodicity of lateral forces is observed, which corresponds to the translational symmetry of the sample material. In a typical experimental situation, as a rule, there is both lateral and longitudinal deformation of the cantilever, but the latter deformation can also be caused by a change in the normal force. It was found that there is always a connection between the corresponding signals in the lateral and normal modes. If this connection is not controlled, then the measurement results are distorted.

Schematically, the principle of measuring the investigated surface by atomic force microscopy is shown in fig. 1.

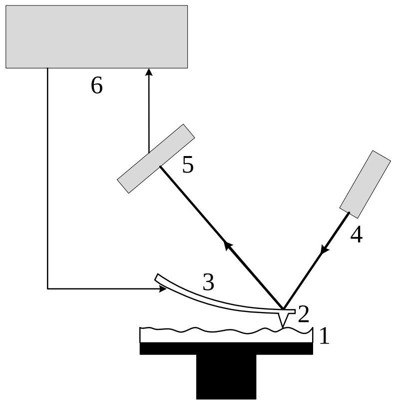

Fig. 1. Block diagram of the principle of measurement of the examined surface in an atomic force microscope: 1 – the examined surface of the sample; 2 – probe (probe); 3 – cantilever; 4 – laser beam; 5 – photodiode; 6 – electronic conversion and feedback device

In an atomic force microscope, a thin probe (2) located at the end of a cantilever beam (3), known as a cantilever, scans the surface (3). High-precision movement of the probe is carried out with the help of piezoelectric elements that change their length under the influence of voltage. When driving over an uneven surface, the dipstick rises and falls. These very small vertical movements are detected with the help of a laser beam (4), which is reflected from the upper surface of the cantilever equipped with a mirror. Even with small displacements, the beam undergoes a large deviation, which can be measured by a matrix photodetector (5).

The received signal is analyzed using an electronic device (6) and converted into an image of the surface of the sample. An electronic feedback mechanism is used to ensure a constant force between the sample surface and the probe and to prevent possible damage.

Knowing the role of the atomic structure in the relative movement of contacting surfaces, researchers tried to explain the "sticking-sliding" effect based on the modernized classical ideas of Tomlinson and the method of molecular dynamics [24]. Since modern models of probes are considered as a collection of point particles with a concentrated mass that has no internal degrees of freedom, or taking into account a multiatomic structure, the visual picture of the "sticking-sliding" effect is significantly simplified.

Initially, the probe is at the minimum point of the potential energy of the "probe-surface" system. This interaction is characterized by a periodic potential that reflects the translational symmetry of the atomic structure of the surface of the part. An essential feature of this model is the assumption of the possibility of applying adiabatic conditions at each step of the probe's movement. In lateral contact loading caused by cantilever scanning, energy is stored in the form of elastic energy of the cantilever-specimen contact. The relative sliding of the probe on the surface of the part sample begins at the moment when the accumulated energy in the material is large enough for the probe to jump out of the potential well and be fixed at another point on the surface. After that, the system relaxes and excess energy quickly dissipates from the contact area through the electron-phonon subsystem. Note that a very short dissipation time is observed, since the characteristic velocities of electrons and phonons (10^{-7} - 10^{-4} m/s) are many orders of magnitude higher than the typical scanning speeds of an atomic force microscopy probe.

Studies show that in order to observe the instability associated with the "sticking-sliding" effect, it is necessary to combine a "soft" cantilever with a "hard" surface of the part sample under the condition of strong interaction. Moreover, more energy dissipates in the case of softer contacts. At that time, the models did not take into account possible mechanisms of energy dissipation, in which the frictional force is proportional to the speed.

It should also be noted that the oscillatory model of the "probe-surface" system describes this "sticking-sliding" effect only under the condition of critical damping of the cantilever, which is its significant drawback due to the high elasticity of the cantilever. To eliminate this contradiction, Johnson and Woodhouse [25] took into account the elastic stiffness of the contact and found a relationship between the effective stiffness of the "probe-surface" system and the amplitude of the periodic friction force. The weakest point of this rationale is the discrepancy between the point oscillator model and the actual situation with the atomic force microscopy probe. The experimental fact is that the period associated with the "stick-slip" effect coincides with the period of the surface atomic structure. In the mode of contact lateral mode of atomic force microscopy, it is possible to talk not about the actual atomic rarefaction of the surface of the part, as is the case in the modulation mode, but about the atomic contrast. This is evidenced by the fact that there is no rarefaction of point atomic surface defects in the contact mode.

Molecular dynamics calculations also indicate the presence of the "sticking-sliding" effect and friction without wear at low loads. A decrease in the friction force is observed when the scanning speed increases. The most serious objections related to the results of molecular dynamics calculations related to the interpretation of the "sticking-sliding" effect. Their range of speeds (1-2000 m/s) causes them, which exceeds scanning speeds in atomic force microscopy. At that time, numerical molecular dynamics experiments significantly enrich the understanding of structural changes occurring in the contact zone.

At the same time, clear differences between conservative and dissipative lateral forces acting on the probe should be taken into account. During the movement of the probe corresponding to the friction loop, we are dealing with the maxima of the static force at which the probe begins to slide. When the real atomic structure of the contact zone is unknown, there is no possibility to detect the movement of atoms inside it. It is believed that there will be limited sliding of atoms on the periphery of the contact. This happens even with very small lateral forces. It was found that the observed lateral force cannot be attributed completely to either dissipative or conservative. It contains both of these components.

The lateral contrast recorded when the direction of movement of the probe is reversed is not unusual, since the contrast does not directly show the atomic structure. If the probe is in the extreme right position, the system is already ready for micro-sliding. The system does not care whether the probe continues to move to the right or changes direction to the opposite. In both cases, the force modulus further decreases. As a result, after a sharp decrease in the initial phase of the reverse movement of the probe, the lateral force turns out to be close to zero and the "probe-surface" contact is unloaded. After that, a new growth of the lateral force (modulo) begins, which continues until the beginning of the next sliding cycle. This indicates that sharp changes in the lateral force are irreversible and are associated with the dissipative nature of the sliding process in the triboconjugates of the "probe-sample of parts".

The atomic periodicity of the "sticking-sliding" effect can be qualitatively explained by the model of the formation and breaking of adhesive bonds. At each position of the probe on the surface of the part sample, the contact spot covers a certain part of it. Moreover, for a spot of a given shape, the number of surface atoms under it varies depending on the lateral coordinates with the lattice period of the surface material. If the probe is located in relation to the surface of the part sample at a point corresponding to the minimum number of adhesive bonds near the boundaries of the contact patch, then during its sharp micro-slip the dissipative force of friction will be minimal, due to the fact that the number of broken and newly created adhesive bonds is relatively small Small discrete jumps and a fine structure of the lateral force are not accompanied by a loss of stability of the triboconjugation of the "probe-sample parts" that continue to accumulate energy. In the position that corresponds to the maximum number of bonds along the boundaries of the contact spot, their rupture as a result of microslipping with a subsequent sharp drop in the lateral force on the cantilever becomes catastrophic. At this moment, the probe breaks off. Old adhesive bonds behind the contact spot are broken, reducing the resistance to the translational movement of the probe, and new ones arising in front of the contact spot capture it forward. The nature of this movement can be described by the model of "atoms-magnets", which are arranged on the surface in the form of a regular lattice and have a vertical degree of freedom, and the probe, which has a flat shape, is installed on a pendulum suspension, the axis of which moves with a constant horizontal speed. This model allows you to visually visualize the atomic "sticking-sliding" effect at the macro level.

Adhesion effects are of significant importance in the problem of nanotribology (atomic friction), as they determine the contact area and interaction of sample parts, as well as their interaction with the probe. Adhesion forces can be directly measured by atomic force microscopy using the lead-pull mode of the probe, or by measurements of friction force-load force relationships.

If contact mechanics is used to substantiate the obtained data, then two main parameters can be used to substantiate the regularities of the "sticking-sliding" processes: shear stress and work of adhesion. The shear stress is proportional to the critical lateral force that causes the probe to slide in the "stick-slide" mode. The work of adhesion is equal to the specific energy related to the unit of tribojunction contact area of the "probe-sample of parts" required for its rupture:

$$\gamma = \gamma_1 + \gamma_2 - \gamma_{12}, \tag{1}$$

where $\gamma_1, \gamma_2, \gamma_{12}$ are the specific surface energies of the probe, the part sample, and the interfacial energy of their contact, respectively.

Let's consider questions related to the dependence of the specified values on the atomic structure of the contact, temperature, external pressure, chemical composition, and the material of the part sample. But at the same time, we take into account the differences between model representations of "dry" vacuum conditions and the more complex case of a "wet" surface, when intermolecular forces can change significantly due to the presence of solvent or solute molecules.

In the case of "dry" friction, the work of adhesion is determined by the separation force of the atomic force microscopy probe from the surface of the part sample. The pull-off force, which is negative in sign, corresponds to the force applied to the cantilever required to separate the surfaces. In the theory of Johnson-Kendall-Roberts [12] for elastic adhesive contacts of soft materials and a probe of a parabolic profile with a radius of curvature R_z , the separation force is equal to:

$$F_{sep} = -1{,}5\pi R_z \gamma \,. \tag{2}$$

Characteristic of the Johnson-Kendall-Roberts theory is that it describes the elastic contact of materials with a strong short-term (attractive) adhesive interaction. The contact of rigid materials with long-range attraction is better described by the Deryagin-Mullier-Toporov theory [11], and the numerical coefficient in expression (2) can be replaced with 1.5 by 2.

In the Johnson-Kendall-Roberts approximation, the ratio for the residual friction force F_{res} at the critical point of probe separation and work of adhesion is:

$$F_{res} = \pi\tau \left(\frac{9\pi R_z^2 \gamma}{8E_{coc}} \right)^{2/3}, \tag{3}$$

where τ is the shear stress, $E_{coc} = (1-\eta_1)/E_1 + (1-\eta_2)/E_2, E_{1,2}$ is the composite modulus of elasticity of the tribocoupled components of the probe materials and sample parts. In the Deryagin-Mullier-Toporov theory $F_{res} = 0$, the separation force corresponds to the van der Waals force of gravity, and for the contact of a spherical probe with a flat surface, we have:

$$F_{sep} = \frac{H_G R_z}{6h_{sep}^2}, \tag{4}$$

where H_G - became Hamakera, R_z – probe radius, h_{sep} – the distance between the probe and the surface of the sample (parts) at the time of separation. Typical values of h_{sep} lie within 0.2...0.3 nm, and constant H_G – in the range of 0.6...2 5 eV.

It was found that friction and adhesion processes are sensitive to changes in the structure of tribocouple materials and chemical interactions in the contact zone. This behavior takes place regardless of changes in the shape of the probe. The peculiarities of the mentioned processes can be explained by chemical or structural changes in the contact zone induced by the scanning of the probe. It is assumed that similar changes in friction and adhesion can be caused by a change in the nature of the proportionality of the probe materials and samples of details of the contacting surface structures.

The weak dependence of the shear stress on the value of the work of adhesion is unusual, since most often there is a linear proportional relationship between these values, in the absence of wear. The simplest model explaining this dependence is the "cobblestone" model, which is equivalent to Tomlinson's model [24]. The sliding of contacting surfaces should be considered similarly to the rolling of a wheel. At rest, the wheel falls into the depression formed by the paving stones, so in order to set it in motion, it is necessary to apply a lateral force sufficient for the wheel to get out of the hole. In this model, the role of surface attractive forces is played by gravity. For an atomically smooth surface, cobblestones correspond to atoms. A similar picture will be for the contact structure of the parts samples. Experimental studies performed on "sticking-sliding" on surfaces, layers of liquid molecules, confirm this model. It was also found that for systems of chain molecules, the work of adhesion increases in the case when conjugated surfaces are in contact with each other. There is also a hysteresis of the contact area during the approach and separation of the mating surfaces, and the friction force increases with an increase in the contact area.

The relationship between the processes of friction and adhesion determined by the internal molecular structure was determined. For dry tribocontacts of materials, adhesive and frictional hysteresis should not be observed [1,26]. There is a model that establishes the relationship between shear stress and adhesion work (in the case of dry contacts). The correlation between the macroscopic values of the surface energy of materials and their shear modulus per atomic radius for homogeneous contacts was determined (Fig. 2).

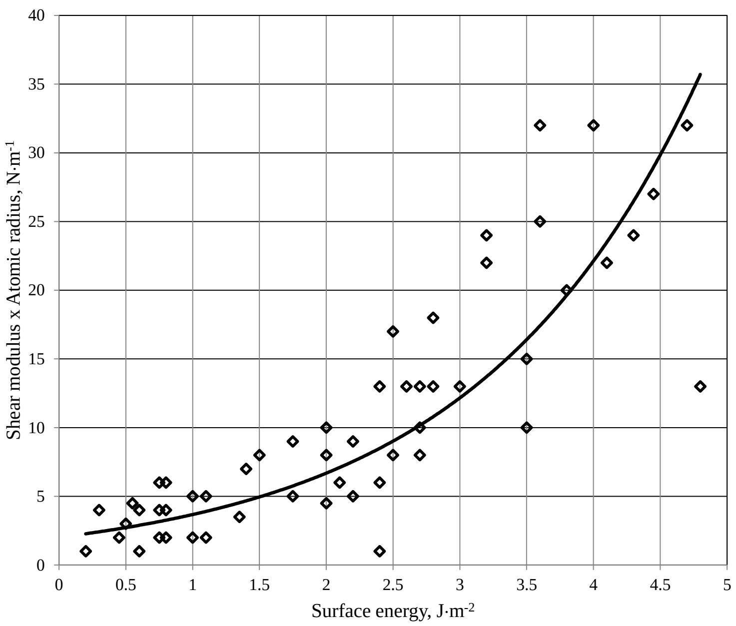

Fig. 2. Correlation between the value of the macroscopic shear modulus per atomic radius and the surface energy of homogeneous contact materials

Since the shear modulus is directly proportional to the shear stress, it can be assumed that the values of G and τ change in a consistent manner. Figure 2 shows equally the correlation between the values τ and γ. This correlation shows that it is possible to distinguish two groups of materials with different proportionality coefficients between τ and γ, due to a non-linear dependence. In this case, it is close to quadratic: $\tau \approx \gamma^2$. The results of the research claim that special attention should be paid to the comparative comparison of the value of the work of adhesion, which is measured using the atomic force microscopy method, with the expected macroscopic values of this value, and a similar comparison for the shear stress values.

In order to obtain the observed extremely low values of the work of adhesion, it is possible to assume in accordance with formula (1) that the equality holds:

$$\gamma_{12} = \gamma_1 + \gamma_2 . \quad (5)$$

High values of γ_{12}, in turn, should indicate a very strong rearrangement of the atomic structure of the interphase boundary, which is unlikely in the case of contacts of solid materials. For the contact of conjugates of samples of parts from homogeneous materials, we have $\gamma_{12} = 0$.

The assumption that the order of magnitude of the macroscopic characteristics of materials when moving to the nanoscale is preserved is not entirely obvious. This follows from the analysis of values of work of adhesion in experimental studies. Much more complex adhesive effects are observed in the case of "wet" tribocontacts. It should be noted that the measurements were carried out in the "input-outlet" modes. The application of atomic force microscopy methods and techniques in this case is particularly promising. At that time, the observed solvation forces require further research.

In the process of experimental research, a linear correlation was found between the macroscopic values of the surface energy, which is measured by the marginal wetting angle, and the friction forces. Due to the small size of the contact zone of the atomic force microscopy probe with the surface, quantization of adhesive forces was detected. The probability of locating the probe at a distance s from the surface of the sample has the character of the Boltzmann distribution:

$$p(S) \sim \exp\left[-\frac{W_P(s)}{k_B T}\right], \tag{6}$$

where $W_P(s)$ is the potential energy, k_B and T is the Boltzmann constant and the thermodynamic temperature. The minima of potential energy $W_P(s)$ had a periodicity of 0.15-0.3 nm.

A large number of other adhesive effects were observed by modeling methods: the formation of adhesive avalanches, plastic flow of the probe material with the formation of crow ions and the generation of dislocations, the vibrational mechanism of compression and destruction of metal nanoparticles during an inelastic impact. Of course, there are certain contradictions between experimental studies and the results of molecular dynamics modeling: experimental studies, unlike molecular dynamics calculations, do not always reveal hysteresis of adhesive forces.

Nanotribological substantiation of the effects of "sticking-sliding" from the point of view of adhesion indicates that it is possible to create conditions for the functioning of couplings of parts of machines and mechanisms when frictional forces are minimal [23,24] . This condition determines the maximum wear resistance, and therefore reliability, and the maximum efficiency of the functioning of machines and mechanisms.

Conclusions

1. It has been found that the study of nanotribological processes in the materials of the samples and parts of machines and mechanisms should be carried out by the methods of the surface force apparatus, scanning tunneling microscopy, and interpreted by the methods of molecular dynamics and classical contact mechanics.

2. During the consideration of theoretical models of the tribon level, much attention is paid to "dry" adhesive and non-contact dynamic friction. At the same time, the effects of "ploughing" and "wet" friction, thermodynamic aspects of nanotribology are taken into account, physical processes in tribocontacts are discussed: "sticking-sliding", damping of motion of adsorbed films, adhesive, chemical and others. The evolution of the structure of nanocontacts is analyzed by the method of molecular dynamics.

3. At the atomic level, the nanotribocontact effect of the conjugated surfaces of the "sticking-sliding" parts samples was considered, with the measurement and analysis of the magnitude of the lateral and normal forces acting on the probe. Various combinations of probe materials and samples of parts were subject to investigation. The "sticking-sliding" effect was detected by the surface forces apparatus, which is characteristic of the translational symmetry of the material of the parts samples.

4. An attempt was made to explain the "sticking-sliding" effect based on the modernized classical ideas of Tomlinson and the method of molecular dynamics. The probe was considered as a set of point particles of concentrated mass, taking into account the multiatomic structure of the material. The contact and movement of the probe with the surface of the sample was considered in the "probe-surface" system with minimal potential energy and under conditions of lateral loading. When exiting the potential well, this system relaxes and excess energy quickly dissipates from the contact region through the electron-phonon subsystem. Both hard and soft contact of the atomic force microscopy cantilever with the surface of the part sample was considered.

5. Differences between conservative and dissipative forces acting on the probe whose movement corresponds to the friction loop are taken into account. It was found that after a sharp decrease in the initial phase of the reverse movement of the probe, the lateral force is close to zero and the "probe-sample surface" contact is unloaded. Sharp changes in the lateral force are irreversible and are associated with the dissipative nature of the sliding process.

6. It is shown that the atomic periodicity of the "sticking-sliding" effect can be explained by the model of the formation and breaking of adhesive bonds. Old adhesive bonds behind the contact spot are broken, reducing the resistance to the translational movement of the probe, and new ones arising in front of the contact spot capture

it forward. This can be described by the model of "atoms-magnets", the system of which moves with a constant horizontal speed and visualizes the atomic effect of "sticking-sliding" at the macro level.

7. Adhesion effects play a significant role in nanotribology, as they determine the contact area and the interaction of the samples with each other and with the probe in the mode of "input-withdrawal" of the probe and measurement of "friction force-load force" dependencies. It is shown that the parameters: shear stress and specific work of adhesion can be used to substantiate the regularities of the "sticking-sliding" processes. The first parameter is proportional to the critical lateral force, and the second is equal to the specific energy relative to a unit of contact area. The work of adhesion is considered both for "dry" and "wet" friction. The Johnson-Kendel-Roberts theory and the Deryagin-Mullier-Toporov theory were used to explain the elastic adhesive contacts for the residual friction force and the probe separation force.

8. It is shown that there is a connection between the processes of friction and adhesion, which is due to the internal molecular structure and frictional hysteresis is observed. The correlation between the macroscopic values of the surface energy of materials and their shear modulus for homogeneous contacts, as well as between the tangential stress and the specific work of adhesion was determined. The substantiation of adhesive effects and the effect of "sticking-sliding" testify to the possibility of controlling the force of friction and creating conditions when the force of friction is practically absent. This state is characterized by maximum wear resistance, and therefore high reliability and maximum efficiency of tribocouplings of parts of machines and mechanisms.

References

1. Aulin V.V. Tribophysical basics of increasing the wear resistance of parts and working bodies agricultural machinery [dys. ... d-ra tekhn. nauk: 05.02.04]. 2014. 447 s. [Ukrainian]
2. Aulin V.V. Physical basis of processes and states of self-organization in tribotechnical systems: monograph / V.V. Aulin. – *Kirovohrad: Ed. V.F. Lysenko*, 2014. 370 p [Ukrainian]
3. Aulin V.V., Lysenko S.V., Velikodnyi D.O., Sponge A.B. A scale-level approach to the analysis of processes in the materials of tribo-junctions of parts of mobile agricultural and motor vehicles. *All-state interdepartmental scientific and technical collection. Design, production and operation of agricultural machines*, Vol. 47, ch.I. Kropyvnytskyi: National Technical University, 2017. P.52-59 [Ukrainian]
4. Atomic force microscope and method for imaging surfaces with atomic resolution: pat. US4724318A, Appl. 09.02.88 [English]
5. Butt H.-J., Cappella B., Kappl M. Force measurements with the atomic force microscope: Technique, interpretation and applications. *Surface Science Reports*. 2005. Issue 59, No. 1-6. P.1-152 [English]
6. Lanza M. Conductive Atomic Force Microscopy: Applications in Nanomaterials. *John Wiley & Sons*, 2017. 382 p [English]
7. Cappella B., Dietler G. Force-distance curves by atomic force microscopy. *Surface Science Reports*. 1999. Vol. 34, No. 1-3. P. 1-104 [English]
8. Scherge M., Gorb SN, Stone HA Biological micro- and nanotribology: nature's solutions. 2002 [English]
9. Tkachuk M.M., Saverska M.S., Kutsenko S.V. Theoretical foundations of contact interaction research and elastic -plastic deformation of machine elements for military and civilian purposes. *Bulletin of the National Technical University "KhPI". Series: Mechanical engineering and CAD*. 2022. No. 1. P. 139-147 [Ukrainian]
10. Nagaraj M.H. et al. Nonlinear analysis of compact and thin-walled metallic structures including localized plasticity under contact conditions. *Engineering Structures*, 2020, vol. 203, pp. 109819 [English]
11. Muller V.M., Yushchenko V.S., Derjaguin B.V. On the Influence of Molecular Forces on the Deformation of an Elastic Sphere and Its Sticking to a Rigid Plane / VM Muller. *J. Coll. Interface Sci*. 1980. V.77. P. 91-101 [English]
12. Johnson K.L., Kendall K., and Roberts A.D. Surface Energy and the Contact of Elastic Solids. *Proceedings of the Royal Society of London. Series A, Mathematical and Physical Sciences*, 324(1558):301–313, Sept. 1971 [English]
13. Muller C. AFM Assisted Nanomanipulation. 2019 [English]
14. Viljoen A., Mathelié-Guinlet M., Ray A., Strohmeyer N., Oh YJ, Hinterdorfer P., Müller DJ, Alsteens D., Dufrêne YF Force spectroscopy of single cells using atomic force microscopy. *Nature Reviews Methods Primers*. 2021. Issue 1, No. 1. P. 63 [English]
15. Hærvig, J., U. Kleinhans, C. Wieland, H. Spliethoff, AL Jensen, K. Sørensen, and TJ Condra. On the adhesive JKR contact and rolling models for reduced particle stiffness discrete element simulations. *Powder Technology*, 319:472–482, 2017 [English]
16. Carr, MJ, W. Chen, K. Williams, and A. Katterfeld. Comparative investigation on modeling wet and sticky material behaviors with a simplified JKR cohesion model and liquid bridging cohesion model in DEM, *ICBMH 2016 - 12th International Conference on Bulk Materials Storage, Handling and Transportation, Proceedings*, pages 40-49, 2016 [English]
17. Johnson K.L. Contact Mechanics. *Cambridge, UK: Cambridge University Press*, 1987. 464 p [English]
18. Zavarise G., M. Borri-Brunetto, Paggi M. On the resolution dependence of micromechanical contact models. *Wear*, 2007, vol. 262(1), pp. 42–54 [English]

19 . Tkachuk MM, Skripchenko N., Tkachuk MA, Grabovskiy A. (2018). Numerical methods for contact analysis of complex-shaped bodies with account for non-linear interface layers. *Eastern-European Journal of Enterprise Technologies*, 5/7 (95), pp . 22-31 [English]

20. Belaidi S., Girard P., Leveque G. Electrostatic forces acting on the tip in atomic force microscopy: Modelization and comparison with analytical expressions. *Journal of applied physics*. 1997. Vol.81, No.3. P.1023-1030 [English]

21. Schitter G., Menold P., Knapp H., Allgöwer F., Stemmer A. High performance feedback for fast scanning atomic force microscopes. Review of Scientific Instruments. 2001. Vol. 72, No. 8. P. 3320–3327 [English]

22. Gates RS, Reitsma MG, Kramar JA, Pratt JR Atomic force microscopy cantilever flexural stiffness calibration: Toward a standard traceable method. *Journal of Research of the National Institute of Standards and Technology*. 2011. Issue 116, No. 4. P. 703 [English]

23. Fujisawa S, Sugarawa Y, Morita S Philos. Mag. A 74 1329 (1996) [English]

24. Tomlinson I Philos. Mag. 7,905 (1929) [English]

25. Johnson KL, Woodhouse J. Trib. Lett. 5 155 (1998) [English].

26. Aulin V. V., Lysenko S. V., Hrynkiv A. V. [and others]. The stressed-deformed state of the surface layer of parts during the implementation of tribotechnologies of run-in and recovery. *Central Ukrainian Scientific Bulletin. Technical sciences: coll. of science pr. - Kropyvnytskyi: National Technical University*, 2019. - Issue 1 (32). - P. 103-113 [Ukrainian]

27. Aulin V., Kuzyk O. Materials of triboelements with different levels of non-equilibrium and conditions for realizing the effect of self-organization. *MOTROL. Commission of Motorization and Energetics in Agriculture*. 2016. Vol.18, No.2. P. 75-82 [Ukrainian]

Аулін В.В., Тихий А.А., Кузик О.В., Лисенко С.В., Гриньків А.В., Жилова І.В., Лівіцький О.М.
Обґрунтування впливу закономірностей протікання нанотрибологічних процесів в матеріалах спряжень деталей на підвищення зносостійкості, надійності та ефективності функціонування машин і механізмів

В статті з'ясовано сутність нанотрибологічних процесів в матеріалах спряжень зразків деталей методами апарату поверхневих сил, скануючої тунельної та атомносилової мікроскопії. Обґрунтування механізмів їх протікання дано методами молекулярної динаміки та класичної контактної механіки. Увагу надано сухому адгезійному і безконтактному динамічному тертю спряжених зразків, фізичним процесам в трибоконтактах "прилипання-ковзання", адгезійні ефекти та ін. Проаналізовані величини діючих на зонд латеральних та нормальних сил. Зонд розглядали як сукупність точкових частинок зосередженої маси з мультиатомною структурою матеріалу. Контакт і рух зонду з поверхнею зразка розглядали в системі "зонд-поверхня" з мінімальною потенціальною енергією та латерального навантаження і врахуванням консервативних і дисипативних сил.

Ефект "прилипання-ковзання" обґрунтовано за допомогою апарату поверхневих сил. Атомарну періодичність ефекту пояснено на основі моделі утворення і розриву адгезійних зв'язків та моделі "атоми-магніти". Показано, що закономірності протікання процесів "прилипання-ковзання" можливо з'ясувати використавши параметри напруження зсуву і питому роботу адгезії.

Для пояснення пружних адгезійних контактів доцільно використати теорію Джонсона-Кендала-Робертса, а для залишкової сили тертя і сили відриву зонду – теорію Дерягіна-Муллєра-Топорова.

Показано, що існує істотний зв'язок процесів тертя і адгезії. Визначено кореляційну залежність між макроскопічним значенням поверхневої енергії матеріалів і їх модулем зсуву для однорідних контактів.

На основі адгезійних ефектів та ефекту "прилипання-ковзання" можна управляти силами тертя і створювати сприятливі умови їх відсутності, що дає підстави отримати високу зносостійкість трибоспряжень деталей, їх надійність та максимальну ефективність функціонування машин і механізмів.

Ключьові слова: адгезійні ефекти, прилипання-ковзання, спряжені поверхні, латеральні сили, тертя, зносостійкість, надійність, ефективність.