Nanotribology: mechanisms of friction on the atomic scale

O.M. Braun*

Institute of Physics, National Academy of Sciences of Ukraine, 46 Science Avenue, 03028 Kiev, Ukraine

A short review of the modern state of the problem of friction from the physical viewpoint is presented. The main attention is devoted to the results obtained by the molecular dynamics method.

I. INTRODUCTION

Science about friction, or tribology (from Greek tribos, that is translated as rubbing) is very important both from scientific and practical points of view. First of all we note that if in one situations it is desirable to reduce friction as much as possible, in others – vice versa, to attain maximally large friction. We remind also that friction may be static and kinetic. The static friction force f_s is the force which one has to apply to initiate sliding. Namely thanks to static friction, we are able to walk and cars to move, as well as mechanical constructions connected by bolts and nuts are stable. The kinetic friction force f_k is the force needed to maintain the smooth sliding with a given velocity v. Therefore, every time unit, the energy $f_k v$ is pumped into the system, which is converted into heat and finally leads to heating of atmosphere. According to estimation [1], the losses of energy because of friction achieve more than 6% of the gross national income in economically developed countries. Therefore, even a small reduction of friction promises an enormous economical effect. In typical situations $f_k < f_s$, for example, $f_k \sim 0.5 f_s$, and the ratio of the friction force to the loading force f_l, $\mu_{s,k} = f_{s,k}/f_l$, known as the friction coefficient in tribology, in order of magnitude takes values of $\mu \sim 0.1$ typically.

Because of importance of friction, its study began more than three centuries ago [2]. The first known study of friction belongs to Leonardo da Vinci (1452-1519) who discovered that the friction coefficient does not depend on the area of contact. Later Guillaume Amontons (1663-1705) showed that the friction is directly proportional to the load, i.e., to the weight of sliding block. Leonhard Euler (1707-1783) noted that one has to distinguish the static friction studied by Vinci, and the kinetic friction explored by Amontons. Finally, Charles Coulomb (1736-1806) discovered that the kinetic friction does not depend on the sliding speed.

These laws, getting the name of the Amontons laws, remained purely empirical up to a middle of past century, when Bowder and Tabor [3] made the first attempt of their explanation from the physical point of view. They paid attention to the fact that the contacting surfaces are almost always rough. Therefore, the real contact is attained only on asperities. An estimation [1] shows that the real area of contact A_{real} makes only $\sim 10^{-5}$ of the geometrical (visible) area A_{vis}. The contacts themselves are under the extremal condition of enormous pressure – forces in the contacts are close to the limit of plasticity of materials that form the contact. This explains the Amontons laws: with the increase of the load f_l, the real contact area grows either due to the increase of the number of contacts (in the regime of elastic response of the system), or because of the plastic deformation of contacts. In the result, the ratio $\mu = f_{s,k}/f_l$ remains approximately constant [4].

Later, more careful experiments showed that the Amontons laws are valid approximately only, and the problem of friction is essentially more involved. Firstly, friction does depend on the sliding velocity. Secondly, it depends on the prehistory of the contact, i.e., friction occurs to be different for a "newborn" contact and for the contact which already undergone some sliding. A new era in the study of friction began only 15-20 years ago, thanks to development of new experimental methods (first of all, the "tip-based technologies" coming from surface physics – the scanning tunnel microscope (STM) [5] and its subsequent improvements – the atomic force microscope (AFM) [6] and the friction force microscope (FFM) [7]), and also due to great progress in computer power allowing to simulate real tribosystems by the molecular dynamics (MD) method.

In this brief survey we present a modern view on the problem of friction from the physical viewpoint, making the main accent on the study of kinetic friction by the MD method. We consider the regime of boundary friction only, when the surfaces are separated by a very thin, of few monomolecular layers, lubricant film. We note that such a film is almost always present: it may be either a specially chosen lubricant, or grease (oil), or dust, or wear debris produced by sliding, or water or a thin layer of hydrocarbon adsorbed from air, *etc.* – all this is called the "third bodies" in tribology. Moreover, even if the lubricant film is thick, at the moments of the onset of motion or at its stop, the lubricant is squeezed out from the contact area, and the system turns out into the regime of boundary lubrication.

---

*E-mail: `obraun.gm@gmail.com`; Web: `http://www.iop.kiev.ua/~obraun`

II. SIMPLE MODELS OF FRICTION

In physics, a very large role is played by simple models, which, from one side, correctly describe the basic aspects of the problem and, from the other side, allow either the exact solution or at least a well grounded one with a predicted accuracy. In tribology, there are two such models – the Tomlinson model [8] (see Fig. 1) and the Frenkel-Kontorova (FK) model [9], schematically shown in Fig. 2. Later, a large number of generalized and combined models was proposed as well, description of which can be found, e.g., in the monograph [11]. However, already the simplest model – a single atom placed into the external periodic potential – allows us to understand some important aspects of friction. Let us assume that the periodic potential of the surface can be described by the sinusoidal function with the period $a_s = 2\pi$ and the amplitude $\varepsilon_s = 1$. If we apply a constant force f to the atom, it will remain in rest (in a local minimum of the potential $V(x) = \sin x - fx$) whilst $f < f_s = 1$; thus, the force f_s is an analog of the static friction force. At $f > f_s$ the atom begins to slide over the potential relief. However, if we now reduce the force, the smooth sliding will survive up to the force $f = f_b = (4/\pi)\eta\sqrt{M}$ (here η is the damping coefficient and M is the atomic mass), as the atom can overcome the maxima of the potential relief due to its inertia. The force f_b is the analog of the kinetic friction force. The important result is that the minimal speed v_b, at which the atom can slide due to inertia, is of the "atomic-scale" order, $v_b \sim 50$ Å/ns $= 5$ m/s.
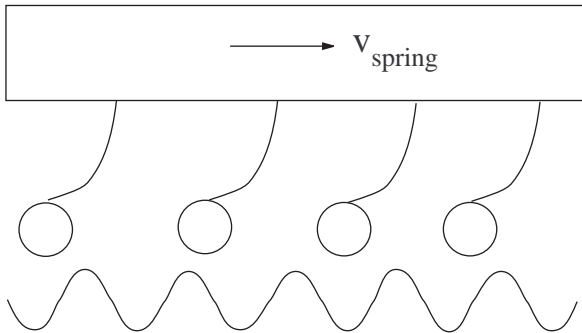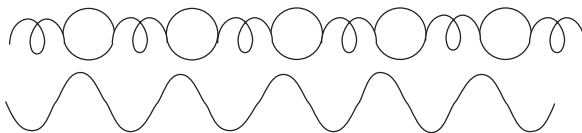

FIG. 1: The Tomlinson model.

FIG. 2: The Frenkel-Kontorova model.

In the tribosystem, the periodic potential corresponds, for example, to the surface potential of the lower (immobile) substrate, while the "atom", to the moving top substrate. As $v_b \propto M^{-1/2}$, one may speculatively suppose that in a macroscopically large system, when $M \to \infty$, we will obtain $v_b \to 0$. This assumption, however, is wrong [12, 13]. At reduction of the driving force, firstly the most lower atomic layer of the top substrate (i.e., the layer nearest to the contact) is stopped, and this takes place at a speed of atomic-scale order. At the same moment, a stopping wave is created, and then the second, third, etc. atomic layers of the top substrate stop successively one after another. The stopping wave takes away the accumulated kinetic energy of motion to the bulk of substrates.

If now we will push the atom not directly but through a spring (which describes, e.g., the elasticity of the top substrate), where the end of the spring moves with a velocity v, we come to the Tomlinson model. At $v > v_b$ the system will demonstrate the smooth sliding, and at lower speeds $v < v_b$ – the so-called stick-slip motion, well known as door creak, bowing a violin, etc. Namely, with the onset of motion the spring stretches and the driving force grows, until it reaches the static threshold f_s. At this moment the system begins to move with the increasing speed, until it catches the end of the spring; thus the spring is weakened again, and the driving force falls down. As a result, the system slows down up to the complete stop, and the whole process repeats itself. In the stick-slip regime, the friction force does not depend on speed; however, if the system temperature is nonzero, $T > 0$, there is a weak (logarithmic) dependence $f(v)$ because of thermally activated jumps of lubricant atoms [1]; another reason for the velocity dependence comes from aging of contacts.

The second important model widely used in tribology is the Frenkel-Kontorova model. First it was proposed for description of dislocations in solids, and then it was widely used in surface physics for description of commensurate and incommensurate structures of films adsorbed on a surface [14]. Generally, a great progress in understanding of friction problems, attained lately, first of all is connected with the progress in surface physics, a large contribution to which was brought by Ukrainian scientists from the Institute of Physics, the Institute of Semiconductors, the Institute of Surface Chemistry, etc. However, the problems in tribology are more difficult, than in surface physics: if the latter studies "opened films" adsorbed on a solid surface, in tribology systems the lubricant film is confined between two surfaces and therefore it is less accessible to direct study.

The FK model describes a chain of interacting atoms (e.g., adsorbed atoms or lubricant atoms), placed in the external periodic potential created by surface atoms of the substrate. A success in the use of the FK model is connected with the fact that in the continuum limit (valid for a strong interaction between the atoms) its equations of motion are reduced to the exactly integrable sine-Gordon equation, the solutions of which, besides the linear waves (phonons), include the topological solitons (so-called "kinks") and dynamical solitons ("breathers"). The kink describes a spatially localized compression of

the chain (or its extension in the case of the antikink), and is characterized by extremely high mobility. Namely kinks are responsible for the fast transfer of mass along the chain, i.e., for mobility of the adsorbed or lubricant film. In two-dimensional (2D) or three-dimensional (3D) systems, conceptions of domain walls or misfit dislocations are used instead of kinks, but the physics of processes remains qualitatively the same. For example, a mechanism of motion of a finite chain (or an island in the 2D system) is the following: a kink is created at one (free) end of the chain, then it rapidly moves along the chain and annihilates on the other chain's end; as the result, the whole chain is displaced on the distance of one lattice spacing [15, 16].

Another extremely important concept of the FK model is the "incommensurability". Namely, if the lattice constants of the chain a and the substrate a_s in the infinite system are incommensurate (i.e., their ratio $\chi = a/a_s$ is irrational), there always exists a critical value of the elastic constant of the chain g, such that for a higher rigidity the chain becomes effectively free of the substrate, i.e., the static friction becomes zero, and the kinetic friction becomes extremely small. This phenomenon (known in physics from the beginning of 1970th as the Aubry transition, or "the transition by breaking of analyticity" [17–21]) acquired an extreme actuality in tribology in connection with the prediction of "superlubricity" [22], i.e., the existence of lubricants providing extremely low friction. In the FK model the best condition for appearance of the state with $f_s = 0$ is achieved at incommensurability corresponding to the "gold section" $\chi = (\sqrt{5} - 1)/2$. If the chain is placed between two one-dimensional "surfaces", the so-called "spiral ratio" of lattice constants turns out the best [23].

Thus, the simple models already provide several answers for the basic questions of tribology, at least on a qualitatively level. For example, it is clear that a solid lubricant could be the most effective: it should provide the maximal friction in the case of commensurate surface/lubricant interface (the so-called "cold welding of contacts") and minimal (up to zero) friction, for the incommensurate interface.

III. MOLECULAR DYNAMICS SIMULATION OF FRICTION

First of all we have to note that in order to obtain realistic values of the friction coefficient, the model system must be three-dimensional. It is connected with the fact that the basic mechanism of energy losses at sliding is excitation of phonons [1, 10]. The rate of this process is directly proportional to the density of phonon states which cannot be correctly described by the one- or two-dimensional system. In other, the modelling of tribosystems is carried out by standard MD methods. The bottom and top substrates are modelled by one or a few atomic layers each, and the lubricant atoms

(or molecules) are placed between the substrates (see Fig. 3). It is assumed that all atoms interact between themselves. The interaction is described, for example, by the Lennard-Jones potential or by a more realistic for the given system potential. The periodic boundary conditions are used in the longitudinal directions x and y. The bottom substrate is fixed (immobile), and a load force (which corresponds, e.g., to the slider weight) and the driving force are applied to the top substrate, usually through a spring, the end of which moves with a given velocity v. During simulation the spring force, which corresponds to the friction force, as well as other parameters, such as the thickness of the lubricant film, its structure, distribution of temperature and atomic velocities through the contact, etc., are monitored.
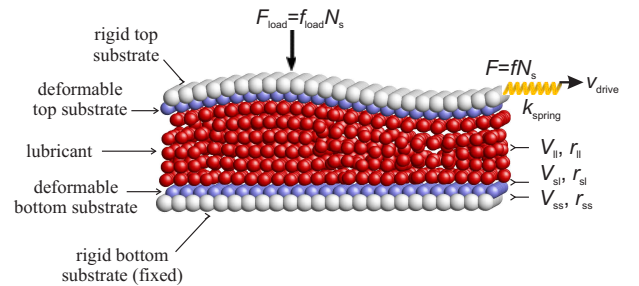

FIG. 3: MD simulation of friction.

The modelling of tribosystems has, however, two important features. Firstly, as the number of lubricant atoms is fixed, the results of simulation may be sensitive to the number of lubricant atoms N, for example, whether the lubricant atoms form exactly two atomic layers or two layers with a half. To reduce related errors, one may make one or both surfaces "corrugated" as shown in Fig. 3 (that, by the way, is closer to real situations, where surfaces are often rough). Besides, it is desirable to make a set of MD simulations with different numbers N.

The second problem in modelling of friction is more serious. We remind that a tribological system is a "machine" to convert the energy of translational motion into heat. Namely, the driving force pumps energy into the system, and if we will not remove it, soon the system will simply evaporate or burst. Therefore, using of solely Newtonian equations of motion is impossible; it is not possible also to use artificial methods of removing energy (such as, e.g., the widely used method of renormalization of atomic velocities at every or a few MD steps), as the rate of energy removing will finally determine the friction force. An ordinary receipt in such a situation is to model the substrates as made of many atomic layers, and then to use the Langevin equations with damping coefficient which smoothly increases with the distance from the interface, thus modelling an effectively "infinite" substrate [13]. However, this method leads to a catastrophic increase of the system size, the more so unjustified, that in the end only the trajectories of lubricant atoms are of

real interest.

A solution of this problem was proposed in Ref. [24]. It consists in the use of Langevin equations for all lubricant and substrate atoms, but with a "realistic" damping coefficient, which depends on the coordinate r_a and velocity v_a of the given atom relatively the surfaces in contact, and correctly describes the energy exchange between the moving atom and the substrates. For the dependence $\eta(r_a, v_a)$, it was proposed to use the expression found earlier for an adatom vibrating near the surface [25, 26]. Of course, the extension of the dependence obtained for vibration of a single adatom to the system of interacting moving lubricant atoms, can result in some errors, but in any case this approach is much better, than to use as the damping coefficient η some arbitrary constant, as in majority of MD simulation of friction [27]. The use of the velocity-dependent damping coefficient requires in turn a substantial development of the method of stochastic equations, as has been done in Ref. [28].

The use of the described MD method showed [10, 24] that the basic factor which determines the behavior of a tribosystem, is the relation between the amplitude of interatomic interaction in the lubricant V_{ll} and the interaction of lubricant atoms with the substrate V_{sl}. In the case of traditional (e.g., oil) lubricants, the inequality $V_{ll} < V_{sl}$ holds, i.e., the lubricant atoms are coupled to the surfaces much stronger, than between themselves; it is the so-called "soft" tribosystem. In the opposite case of the "hard" system, the interaction of lubricant atoms between themselves is strong, $V_{ll} > V_{sl}$, and as the result, the lubricant remains in the solid state even at sliding.

IV. MELTING OF A THIN LUBRICANT FILM

As is well known from surface physics, mechanisms of melting of the monoatomic film adsorbed on a crystal surface essentially differ from those in bulk, and are characterized by a large variety [29]. The same is true for the lubricant film confined between two surfaces. The first and obvious fact is that the temperature of melting of the lubricant film T_c is essentially higher, than the bulk melting temperature T_v [30]; for example, for a monolayer film the ratio T_c/T_v may achieve a value of 3. The value of T_c monotonically decreases with the increase of the number of layers N_l in the lubricant film and approaches the bulk value only for $N_l > 5$. T_c grows also with the increase of pressure. Such a behavior is related to the limitation of motion of lubricant atoms in the transverse direction because of the contact with the surfaces.

The mechanisms of melting of the hard and soft lubricants are also different [31]. In the hard tribosystem, the lubricant atoms in contact with the substrates can vibrate with a larger amplitude than in the middle of the film; therefore its melting begins from the boundary layers. In the opposite case of the soft lubricant, where the boundary layers are strongly coupled with the substrates, the melting begins from a middle of the film. The $T_c(N_l)$

dependence obtained with the MD simulation can be well explained theoretically with the help of the Lindemann criterion [31]. In both cases, however, the melting is related to the increase of the specific volume, that in the tribosystem, as the MD simulation shows, is expressed in a sharp increase of the film thickness and formation of an additional atomic layer.

Properties of the molten lubricant film differ from those of the bulk liquid – the former demonstrates a well defined layered structure, which is saved at sliding as well. Although the discovery of this fact caused the surprise in tribology community, from the surface physics viewpoint this phenomenon is obvious: the crystalline structure of the surfaces imposes a structure to the nearby layers of the liquid lubricant both in the transverse and, in less degree, in the longitudinal directions x and y (the latter, however, is destroyed at sliding).

It is interesting that in the solid state at $T < T_c$ the film structure also substantially differs from that in the bulk: although the state is "solid", as the shear module is nonzero, mobility of atoms in the film considerably exceeds that in the bulk, as characteristic for the same temperature. It is related to the presence of a large number of defects (e.g., vacancies) in the confined film, so that the state of the film is closer to a glasslike, than to the ideally crystalline.

Finally, we note that the lubricant film can be melted not only because of the rise of temperature, but also due to sliding (the sliding-induced melting). The mechanism of this melting, however, differs from that described above [32].

V. KINETIC FRICTION

Although it may seem strange, the problem of static friction is considerably more difficult, than the problem of kinetic friction. For example, theory predicts [33] that almost always the static friction should be zero for the contact of two elastic substrates, that totally conflicts with all known experiments. The difficulties of f_s calculation emerge because the static friction is determined by the concrete structure of the contact, which may be quite complicated and badly defined (for example, it is supposed that it rather corresponds to a glasslike structure). Besides, the values of thresholds may differ from contact to contact, as well as change in time (typically f_s grows with the time of stationary contact – the so-called aging of contacts – probably, because of their plastic deformation). Therefore, below we discuss the problem of kinetic friction only, i.e., the regime of smooth sliding, when the system is in the well definite steady state. We remind that this regime corresponds to quite high sliding velocities, $v > v_c \sim 1 - 10$ m/s.

In the case of a traditional (oil-based) lubricant, or the soft tribosystem, the boundary layers of the lubricant film are strongly coupled to the surfaces and, therefore, sliding must begin with rupture of bonds somewhere in

the middle of film. As a result, the film is melted with the onset of motion, and remains liquid both in the smooth sliding regime (at $v > v_c$) and in the sliding phase of the stick-slip regime at $v < v_c$. In the latter case, the film freezes again during the stop of motion; such a mechanism of stick-slip motion is called the melting-freezing mechanism [34, 35]. In the smooth sliding regime, the liquid state of the film is supported due to its heating because of sliding. However, a detailed MD study shows that there are two different sliding regimes, the "liquid-sliding" (LS) regime described above, and the "layer-over-layer" sliding (LoLS) regime, when the lubricant layers keep an ordered structure at sliding (this reminds turbulent and laminar flows in hydrodynamics). The friction coefficient in the soft system takes on intermediate values of order $\mu \sim 0.1$, and μ is directly proportional to the viscosity of lubricant, which for a thin film may be either lower or in $2 - 3$ times higher than the bulk viscosity [10, 24].

On the other hand, in the case of solid lubricant, or the hard tribosystem, the sliding takes place at the surface/lubricant interface (usually only at one of the two boundaries, as the system is rarely fully symmetric). And if the surface and the hard lubricant have an ideal crystalline structure, we get the system with extremely low friction. This occurs because the substrate and lubricant are, as a rule, rigid enough, so that their rigidities are above the Aubry threshold, so that the sliding mode is realized. Besides, the substrate and lubricant are made of different materials typically, therefore they have different lattice periods, incommensurable in a general case. But even if the periods coincide or are commensurate, the commensurate interface in the two-dimensional contact can be formed only if the axes of these two lattices are strictly aligned, because any, even smallest dismiss of the axes will result in incommensurability of the lattices. Thus, the regime of extremely low friction should be realized practically always if, we emphasize, the substrates and the solid lubricant have the ideal crystalline structure [10, 24]. Namely this fact explains the very good tribological characteristics of the graphite-based lubricants as well as other layered materials such as MoS_2 and Ti_3SiC_2. Extremely low friction is indeed observed experimentally, for example, at scanning of the W(011) tip on the Si(001) surface [36], or for sliding of a graphite scale on the graphite surface [37]. We note that a large progress in development of hard lubricants was achieved at the Institute of Material Problems NASU [38, 39].

However, the described above advantages of the solid lubricants disappear completely, if the contacting surfaces are not ideal, for example, if there are steps, asperities or other defects on the surfaces, where the pinning (hooking) of the surfaces takes place. At depinning from these defects, the lubricant may be melted, and then, during the stop, it will be solidified again, but already with a structure close to amorphous one, as the cooling of the confined film is very rapid due to a good thermal contact with the substrates. In the case of imperfect (amorphous or glasslike) structure of the solid lubricant film, the friction becomes quite large, larger than for liquid lubricants [10, 24].

Nevertheless, by the careful choice of parameters of the solid lubricant it is possible to recover its good tribological characteristics. We remind that the lubricant is heated to some temperature T_{slide} at sliding, and also that its melting temperature T_c is proportional to the amplitude of the interatomic interaction V_{ll}. If we will chose the V_{ll} parameter so that T_{slide} be close to T_c (but do not exceed it), structure defects of the film may be removed (annealed), and the film may self-order during sliding. The MD simulation [40] confirms the possibility of such a scenario: starting from an imperfect film, we observe the stick-slip motion. The film temperature sharply rises during the phase of sliding, the film self-orders remaining in the solid state and, after a few stages of sliding, the system passes to the smooth sliding regime with a very low friction. For realization of the self-ordering mechanism, it is necessary to choose the amplitude V_{ll} of the interaction large enough, so that the film is not melted during sliding, but not too large, so that the rate of annealing of defects is not too low.

The results of the MD modelling allowed us also to build the phenomenological theory of kinetic friction [10], by which it is possible to predict analytically the behavior of a tribosystem with the change of its parameters.

VI. FROM ATOMIC-SCALE TO MACROSCOPIC FRICTION

The described above atomic-scale mechanisms of friction are for sure important in designing nano-mechanical devices. However, there arises a question of are they in any relation with the friction in macrosystems. Foremost the value of the critical velocity of the transition from stick-slip to smooth sliding causes suspicion: at experiment the transition is observed at velocities about $1 - 10$ μm/s [1, 41], while the MD simulation leads to values $v_c \sim 1 - 10$ m/s and, as proved in Ref. [13], this value cannot be substantially lower. We note, however, that a more careful an experiment be carried out, the higher values of v_c are obtained [42]. The second problem is related to the viscosity of the thin lubricant film: MD simulation predicts that viscosity of the film can be higher by the bulk value in $2 - 3$ times only, while the experiment shows their difference on many orders of magnitude. These two problems, however, are linked together. Indeed, viscosity of the thin film is defined as fd/va_s^2, where d is the film thickness and a_s is the substrate lattice constant [10]. If we insert into this expression instead of v the value v_c taken from experiments, we obtain the declared by experimentalists huge increase of viscosity, as there are no essential difference between the simulation and experiment for other values (forces, film thickness, etc.) [10].

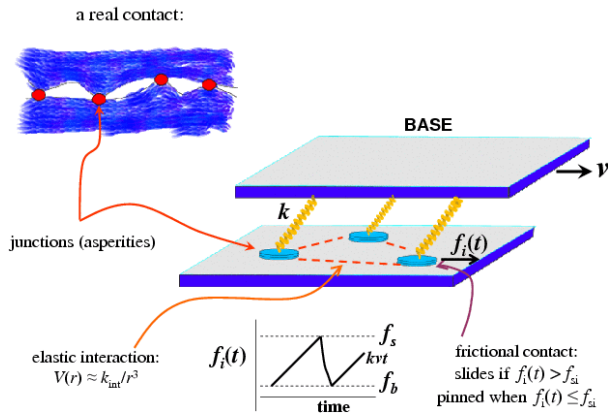This contradiction can be resolved with the help of the

FIG. 4: The earthquakelike model.

earthquakelike (EQ) model – third from the basic models used in tribology. The name of this model appeared because the same type of models is used for modelling of earthquakes [43]. Physics of both processes is qualitatively identical, but differs by the spatio-temporal scale – nanometers and seconds to hours in tribology on comparison with kilometers and years to centuries in geology. In the EQ model the sliding interface is treated as a set of contacts bound by springs with the moving top base (the springs model the elasticity of the top substrate), as shown in Fig. 4. A single contact behaves in accordance with STM experiments or MD simulations: it is immobile until the total force f_i acting on it, does not exceed the static threshold f_{si}. When the threshold is attained, the contact quickly moves to a new position, where $f_i = f_b$ (usually for simplification it is supposed $f_b = 0$). One may also take into account the elastic interaction between the contacts, so that a displacement of one contact causes redistribution of forces on the other contacts, and that can provoke their relaxation as well or even cause an avalanche of relaxations.

The basic issue in the EQ model for description of friction is incorporation of contact's aging (i.e., the threshold f_{si} increases with the contact lifetime counted off from the moment of its last sliding). The aging results in a dependence of system dynamics on the driving velocity [44]. Then, at a low velocity, when all contacts have enough time to "grow old" and attain approximately the same value, depinning of contacts takes place almost simultaneously over the whole system, i.e., their motion is synchronized. It is the stick-slip regime observed in macroscopic experiments. At a high sliding velocity, the threshold values f_{si} for different contacts are different, therefore they move asynchronically and, as a result, the averaged spring force is approximately constant. In the macroscopic experiment, such a motion looks like the "smooth" sliding at which, we emphasize, the contacts themselves are still in the regime of (microscopic) stick-slip. For the contact of rough surfaces, a typical distance between the contacts is $a \sim 10^{-6} - 10^{-3}$ m, and the aging time is of the order of $\tau \sim 1 - 10^3$ sec; thus the change

of sliding regimes should take place at $v \sim a/\tau$, as is observed experimentally.

In the experiments that use the SFA (surface force apparatus [46]) or SFB (surface force balance [42]) technique, the sliding surfaces are made of mica, which may have atomically flat surface of macroscopic area. However, even in this case the lubricant film cannot be ideal throughout the whole contact area – it should be split on domains, e.g., with different orientation, because this will lower the free energy of the system due to the increase of entropy. Domains of different orientations have different values for the thresholds f_{si}, i.e., they play the same role as the contacts in the case of rough surfaces.

Further development of researches in this direction [47] allows us to describe friction on the mesoscopic level, and this is the basic approach in modern material science.

VII. CONCLUSION

Majority from the results described above, as well as many others not included in the given review because of lack of space, were obtained just in the last 5-10 years. This indicates the fast progress in tribology. However, the further improvement of experimental methods, able to fix not only the average friction force but provide also a detailed information about processes inside the lubricant film, is still extraordinarily actual. In this plan, the use of methods already well developed in surface physics, looks very promising. For example, an important information on the energy exchange in adsorbed films can be obtained by the quartz crystal microbalance (QCM) method [48]. From other interesting new experimental methods, one may mention the methods used in works [49–51], and also a recently developed at the Institute of Physics (NASU) technique of "levitating substrate", where a sliding block holds out above the surface by the magnetic field [52].

From the problems not considered in the review, first of all we have to mention the problem of search of methods to control and operate the friction both by chemical methods by adding specially chosen molecules to the base lubricant [53], and by mechanical methods, for example, using special nanopatterned surfaces [54] or applying an external oscillating force to the system [55].

We also did not touch the important question of the form of lubricant molecules. As was shown above, the minimal friction is achieved in the case of contact of two ideal crystalline surfaces. The form of molecules of the hard lubricant in this case is not important, as the main role plays the surface structure. In the case of traditional, or soft tribosystems, the kinetic friction force is directly proportional to viscosity of the liquid lubricant; therefore, a lower is the viscosity, the smaller should be the friction. As a speculative example one may mention the use of air as a "lubricant" between the rotating disk and the reading head in computer disks, where the head "levitates" over the disk like an airplane. Another example known from times of ancient Egypt but recently acquired

the special actuality in connection with development of nano-mechanical devices, is the use of water [56, 57] or water solutions [58] as lubricants. Everybody knows how slippery is the surface of ice covered by a thin water film. One has to note also that in the process of evolution, the nature chose namely water solutions as lubricants in living organisms. However, daily experience says just about reverse: if to smear hands by a butter, they will be far more slippery, than if it is simple to get wet of them, i.e., the experience prompts that often a liquid with a high viscosity is a better lubricant [1]. This is related to squeezing of the lubricant out from the contact area: a higher is the viscosity, the slower is the process of squeezing out. More rigorously, in the case of boundary lubrication, the important is not the lubricant viscosity, but the length L of lubricant molecules: a longer is the molecule, the by the greater number of the atoms it holds on the surface, and the more difficult is to remove it out from the contact area [59]. In some systems, however, the dependence $\mu(L)$ may be nonmonotonic [51]. Another interesting idea is to use advantages of rolling friction, e.g., to use the spherical molecules C_{60} (fullerenes) as a lubricant [60, 61] – as is well known, in macroscopic systems the friction coefficient of rolling is in $10^2 - 10^3$ times lower than the frictions of sliding. For example, lately it becomes actual to design "microcars" able to transport "loads" on the crystal surface [62] and micro-bearing which use carbon nanotubes or fullerenes as rollers.

In conclusion we emphasize that the problem of friction is many-branched and requires the coordinated intra-disciplinary efforts – from the side of physicists, chemists, material scientists and mechanics, and then we may expect a great progress in tribology in nearest future.

[1] Persson B.N.J. *Sliding friction: Physical principles and applications.* Springer-Verlag, Berlin, 1998.
[2] Dowson D. *History of tribology.* Longman, New York, 1979.
[3] Bowden F.P., Tabor D. *Friction and lubrication of solids.* Clarendon, Oxford, 1950.
[4] Greenwood J.A., Williamson J.B.P. *Contact of nominally flat surfaces.* // Proc. Roy. Soc. A. – 1966. – **295**. – P. 300-319.
[5] Binnig G., Rohrer H., Gerber C., Weibel E. *Surface studies by scanning tunneling microscopy.* // Phys. Rev. Lett. – 1982. – **49**. – P. 57-61.
[6] Binnig G., Quate C.F., Gerber C. *Atomic force microscope.* // Phys. Rev. Lett. – 1986. – **56**. – P. 930-933.
[7] Mate C.M., McClelland G.M., Erlandsson R., Chang S. *Atomic-scale friction of a tungsten tip on a graphite surface.* // Phys. Rev. Lett. – 1987. – **59**. – P. 1942-1945.
[8] Tomlinson G.A. *A molecular theory of friction.* // Phil. Mag. Series. – 1929. – **7**. – P. 935-939.
[9] Kontorova T., Frenkel Yu.I. *On the theory of plastic deformations.* // Zh. Exp. Teor. Fiz. – 1938. – **8**. – P. 1340.
[10] Braun O.M., Naumovets A.G. *Nanotribology: Microscopic mechanisms of friction.* // Surf. Sci. Reports. – 2006. – **60**. – P. 79-158.
[11] Braun O.M., Kivshar Yu.S. *The Frenkel-Kontorova model: Concepts, methods, and applications.* Springer-Verlag, Berlin, 2004.
[12] Persson B.N.J. *Theory of friction: The role of elasticity in boundary lubrication.* // Phys. Rev. B. – 1994. – **50**. – P. 4771-4786.
[13] Braun O.M., Peyrard M., Bortolani V., Franchini A., Vanossi A. *Transition from smooth sliding to stick-slip motion in a single frictional contact.* // Phys. Rev. E. – 2005. – **72**. – P. 056116.
[14] Lyuksyutov I.F., Naumovets A.G., Pokrovsky V.L. *Two-dimensional crystals.* Academic Press, Boston, 1992, 423 pp.
[15] Braun O.M. *Activation energy for motion of a linear molecule in periodic potential.* // Kinetika i katalis. – 1990. - **31**. – P. 1356-1360.
[16] Braun O.M. *Adiabatic motion of an atomic chain in periodic potential.* // Surface Sci. – 1990. – **230**. – P. 262-276.
[17] Ying C.S. *Structure and dynamics of a submonolayer film adsorbed on solid surfaces.* // Phys. Rev. B. – 1971. – **3**. – P. 4160-4171.
[18] Sokoloff J.B. *Sliding charge-density waves in periodic and disordered lattices.* // Phys. Rev. B. – 1977. – **16**. – P. 3367-3372.
[19] Pokrovsky V.L., Talapov A.L. // Zh. Exp. Teor. Fiz. – 1978. – **75**. – P. 1151.
[20] Aubry S. // In: *Solitons and condensed matter physics*, Ed. by A.R. Bishop and T. Schneider, Solid State Sciences, Vol. **8**. Springer, Berlin, 1978, P. 264.
[21] Aubry S., LeDaeron P.Y. *The discrete Frenkel-Kontorova model and its extensions: I. Exact results for the ground-states.* // Physica D. – 1983. – **8**. – P. 381-422.
[22] Hirano M., Shinjo K. *Atomistic locking and friction.* // Phys. Rev. B. – 1990. – **41**. – P. 11837-11851.
[23] Braun O.M., Vanossi A., Tosatti E. *Incommensurability of a confined system under shear.* // Phys. Rev. Lett. – 2005. – **95**. – P. 026102.
[24] Braun O.M., Peyrard M. *Friction in a solid lubricant film.* // Phys. Rev. E. – 2001. – **63**. – P. 046110.
[25] Braun O.M. *Energy exchange in adsorbed layers.* // Sur-

face Sci. – 1989. – **213**. – P. 336-358.

[26] Braun O.M., Volokitin A.I., Zhdanov V.P. *Vibrational spectroscopy of adsorbates.* // Uspekhi Fiz. Nauk. – 1989. – **158**. – P. 421-450.

[27] Robbins M.O., Muser M.H. *Computer simulation of friction, lubrication and wear.* // In: Handbook of modern tribology, Ed. by B. Bhushan, CRC Press, Boca Raton, 2000.

[28] Braun O.M., Ferrando R. *Role of long jumps in surface diffusion.* // Phys. Rev. E. – 2002. – **65**. – P. 061107.

[29] Naumovets A.G. *Using surface phase transitions for changing surface properties.* // In: New materials and technologies, Ed. by I.K. Pokhodnya *et.al.*, Akademperiodika, Kiev, 2003, P. 319-350.

[30] Robbins M.O. *Jamming, friction and unsteady rheology.* // In: Jamming and rheology: Constrained dynamics on microscopic and macroscopic scales, Ed. by A.J. Liu and S.R. Nagel, Taylor and Francis, London, 2000.

[31] Braun O.M., Peyrard M. *Dynamics and melting of a thin confined film.* // Phys. Rev. E. – 2003. – *68.* – P. 011506.

[32] Zhukov A.V., Paliy M.V., Braun O.M., George T.F. *Two-stage melting in tribological systems.* // Phys. Lett. A. – 2007. – **361**. – P. 437.

[33] Sokoloff J.B. *Possible microscopic explanation of the virtually universal occurrence of static friction.* // Phys. Rev. B. – 2002. – **65**. – P. 115415-1–115415-9.

[34] Thompson P.A., Robbins M.O. *Origin of stick-slip motion in boundary lubrication.* // Science. – 1990. – **250**. – P. 792-794.

[35] Robbins M.O., Thompson P.A. *Critical velocity of stick-slip motion.* // Science. – 1991. – **253**. – P. 916.

[36] Hirano M., Shinjo K., Kaneko R., Murata Y. *Observation of superlubricity by scanning tunneling microscopy.* // Phys. Rev. Lett. – 1997. – **78**. – P. 1448-1451.

[37] Dienwiebel M., Verhoeven G.S., Pradeep N., Frenken J.W.M., Heimberg J.A., Zandbergen H.W. *Superlubricity of graphite.* // Phys. Rev. Lett. – 2004. – **92**. – P. 126101-1–126101-4.

[38] *Application of composite material "IPM-301" at tribo-functions of space radiometric system "R-400".* / A. Kostornov, A. Yuga, T. Chevichelova, Yu. Simeonova, T. Nazarsky. // Proceedings of Second International Conference "Materials and Coatings for Extreme Performances: Investigations, Applications, Ecologically Safe Technologies for their Production and Utilization". – Kiev: NASU, 2002. – P. 519-510.

[39] Kostornov A.G., Beloborodov I.I., Kovbasenko V.V., Alekseev V.I., Kostenko O.D., Varchenko V.T. *Developing of high-effective materials for atomic power stations.* // In: Safety problems of machines, P. 224-227. – Kyiv, 2006. – 604 pp.

[40] Braun O.M., Paliy M., Consta S. *Ordering of a thin lubricant film due to sliding.* // Phys. Rev. Lett. – 2004. – **92**. – P. 256103.

[41] Yoshizawa H., McGuiggan P., Israelachvili J. *Identification of a second dynamic state during stick-slip motion.* // Science. – 1993. – **259**. – P. 1305-1308.

[42] Klein J., Kumacheva E. *Simple liquids confined to molecularly thin layers. I. Confinement-induced liquid-to-solid phase transitions.* // J. Chem. Phys. – 1998. – **108**. – P. 6996-7009.

[43] Olami Z., Feder H.J.S., Christensen K. *Self-organized criticality in a continuous, nonconservative cellular automaton modeling earthquakes.* // Phys. Rev. Lett. – 1992. – **68**. – P. 1244-1247.

[44] Persson B.N.J. *Theory of friction: Stress domains, relaxation, and creep.* // Phys. Rev. B. – 1995. – **51**. – P. 13568-13585.

[45] Braun O.M., Roder J. *Transition from stick-slip to smooth sliding: An earthquakelike model.* // Phys. Rev. Lett. – 2002. – **88**. – P. 096102.

[46] Israelachvili J.N., McGuiggan P.M., Homola A.M. *Dynamic properties of molecularly thin liquid films.* // Science. – 1988. – **240**. – P. 189-191.

[47] Braun O.M., Peyrard M. *Modeling friction on a mesoscale: Master equation for the earthquakelike model.* // Phys. Rev. Lett. – 2008. – **100**. – P. 125501.

[48] Krim J., Solina D.H., Chiarello R. *Nanotribology of a Kr monolayer: A quartz crystal microbalance study of atomic-scale friction.* // Phys. Rev. Lett. – 1991. – **66**. – P. 181-184.

[49] Budakian R., Putterman S.J. *Correlation between charge transfer and stick-slip friction at a metal-insulator interface.* // Phys. Rev. Lett. – 2000. – **85**. – P. 1000-1003.

[50] Mukhopadhyay A., Zhao J., Bae S.C., Granick S. *Contrasting friction and diffusion in molecularly thin confined films.* // Phys. Rev. Lett. – 2002. – **89**. – P. 136103.

[51] Rubinstein S.M., Cohen G., Fineberg J. *Detachment fronts and the onset of dynamic friction.* // Nature. – 2004. – **430**. – P. 1005-1008.

[52] Kulik V.S., Marchenko A.A., Naumovets A.G., Cousty J. // In: Physics, Chemistry and Application of Nanostructures, Ed. by V.E. Borisenko, S.V. Gaponenko, and V.S. Gurin, World Scientific, Singapore, 2005, p. 74-77.

[53] Mosey N.J., Muser M.H., Woo T.K. *Molecular mechanisms for the functionality of lubricant additives.* // Science. – 2005. – **307**. – P. 1612-1615.

[54] Gang O., Alvine K.J., Fukuto M., Pershan P.S., Black C.T., Ocko B.M. *Liquids on topologically nanopatterned surfaces.* // Phys. Rev. Lett. – 2005. – **95**. – P. 217801.

[55] Zaloj V., Urbakh M., Klafter J. *Modifying friction by manipulating normal response to lateral motion.* // Phys. Rev. Lett. – 1999. – **82**. – P. 4823-4826.

[56] Raviv U., Laurat P., Klein J. *Fluidity of water confined to subnanometre films.* // Nature. – 2001. – **413**. – P. 51-54.

[57] Paliy M., Braun O.M., Consta S. *The friction properties of an ultrathin confined water film.* // Tribology Letters. – 2006. – **23**. – P. 7.

[58] Raviv U., Klein J. *Fluidity of bound hydration layers.* // Science. – 2002. – **297**. – P. 1540-1543.

[59] Sivebaek I.M., Samoilov V.N., Persson B.N.J. *Squeezing molecular thin alkane lubrication films between curved solid surfaces with long-range elasticity: Layering transitions and wear.* // J. Chem. Phys. – 2003. – **119**. – P. 2314-2321.

[60] Braun O.M. *Simple model of microscopic rolling friction.* // Phys. Rev. Lett. – 2005. – **95**. – P. 126104.

[61] Loktev V.M., Pogorelov Yu.G. *Boundary friction on molecular lubricants: rolling mode?* // Fizika nizkikh temperatur. – 2004. – **30**, No.4. – P. 426-430.

[62] Porto M., Urbakh M., Klafter J. *Atomic scale engines: Cars and wheels.* // Phys. Rev. Lett. – 2000. – **84**. – P. 6058-6061.