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Chapter

Structural-Energy Interpretation of the Friction

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Abstract

The structural-energy model of elastic-plastic deformation is considered as the main mechanism of transformation and dissipation of energy under friction. The equations of friction energy balance are proposed. The energy interpretation of the coefficient of friction is given. A structural-energy diagram of the friction surfaces is proposed. The energy regularities of evolution of tribological contact (elementary tribosystem) are discussed. The idea of the smallest structural element of dissipative friction structures (mechanical (nano) quantum) is discussed. Mechanical quantum is dynamic oscillator of dissipative friction structure. The nano-quantum model of the surfaces damping is proposed. Calculations for some Hertzian heavily loaded contacts of real tribosystems are proposed.

Keywords: energy balance, contact evolution, adaptation, dissipation, nanostructure, wear standard

1. Introduction

Modern tribology considers elastic-plastic deformation of friction surfaces as the main mechanism of transformation and dissipation of energy during friction.

The modern view of plastic deformation offers ergodynamics of deformable solids [1–3]. Ergodynamics of deformable solids is a synthesis to the problem of deformation most general laws of thermodynamics for non-reversable processes, molecular kinetics and dislocation theory in their mutual, dialectical tie on the basis of a most general law of nature—the law of energy conservation at its transformations.

The macroscopic phenomenon of plastic deformation, damage and destruction of a solid element is considered as a set of a huge number of microscopic elementary acts of atomic-molecular rearrangements, causing the generation (reproduction) by sources, movement, interaction and destruction of various kinds of elementary defects on the drains. Each defect is a carrier of excess potential energy and on its formation is spent strictly defined work of external forces.

From the thermodynamic point of view, the whole variety of mechanisms and structural levels of plastic flow can be divided into two most characteristic groups— adaptive and dissipative types. The first group should include the mechanism of nucleation and accumulation in the local volumes of various kinds of elementary defects and damages of the structure. The second group includes elementary acts of atomic-molecular rearrangements associated with the movement and destruction of various defects on the drains, that is, controlling the dynamic return.

Such structural-energy interpretation of plastic deformation (friction of contact volumes) determines kinetic and competitive regularities of the process [1–3].

If you apply the basic concepts of plastic deformation of solids this theory for the analysis of the process of friction, it is possible to consider the method of triboergo-dynamics [4].

The major distinction of triboergodynamics from general ergodynamics of deformed solids is "scale factor" which exhibits itself in existence of critical friction volume. This volume determines the limit friction parameters and separate, in essence, the surface deformation from the traditional volume deformation.

In the most general case the triboergodynamics should be seen as structuralenergy interpretation of the friction process. In the framework of triboergodynamics the process of friction is considered as an evolutionary phenomenon of the contact friction (rubbing surfaces).

2. Short fundamentals of ergodynamic of deformed solids

2.1 Structural model of the material

The deformable body is considered as an open, multicomponent, essentially inhomogeneous and nonequilibrium system, representing a hierarchy of statistically uniformly distributed over the volume of metastable structural elements (defects and damages) of various (from macro- to micro-) levels. Some of these structural elements are virtual sources and sinks of elementary defects (vacancies, dislocations, etc.), others—obstacles to their movement.

The main parameters characterizing the structural state of the material are [2, 3]: γ_{σ} is the coefficient of overstress on interatomic bonds, characterizing the uneven distribution of external stresses σ on interatomic bonds $\sigma^{0}(\gamma_{\sigma} = \sigma^{0}/\sigma \ge 1)$; u_{e} is the density of latent (free) energy of defects and damages; v is the coefficient of unevenness of the distribution of latent energy in volume, representing the ratio between the density of latent energy in the local volume u_{e}^{0} to the average value $u_{e}(v = u_{e}^{0}/u_{e})$. The complex structural parameter $k = \gamma_{\sigma}/v^{0.5} = \sigma_{*}/S_{*}$ characterizes the relationship between the theoretical σ_{*} and real S_{*} strength of a solid.

2.2 Physical model and structural-energy interpretation of the process

Macroscopic phenomena of plastic deformation and scattered destruction of the body element are a cooperation of a huge number of microscopic elementary acts of atomic and molecular rearrangements in the field of external (thermal, mechanical, electrical, etc.) forces activated by thermal energy fluctuations. The whole variety of mechanisms and structural levels of the process from the thermodynamic point of view is divided into two most characteristic groups—adaptive and dissipative (relaxation) type, which differ in physical nature and kinetic laws. The first group includes elementary acts that control the origin and accumulation of elementary defects in the deformable body (damageability). The integral characteristic of intensity of the specified processes is specific (referred to unit of volume) power of pumping of excess (latent) energy \dot{u}_e

$$\dot{u}_e = \frac{du_e}{dt} = A \sinh\left[\left(\alpha\sigma_i^2 - \nu \ u_e\right)/2kT\right].$$
(1)

The second group includes mechanisms and elementary acts that control relaxation (dissipative) processes of plastic deformation. The integral

characteristic of these processes is the specific power of the thermal effect \dot{q} of plastic deformation

$$\dot{q} = \frac{dq}{dt} = B \sinh\left[\left(\alpha\sigma_i^2 + \nu \,u_e\right)/2kT\right].$$
(2)

here, *A* and *B* are the kinetic coefficient

$$A = \frac{2kT}{hV_0} \sum_{1}^{n} U'_i(\sigma_0, T) \exp\left[-\frac{U'(\sigma_0, T)_i}{kT}\right],$$

$$B = \frac{2kT}{hV_0} \sum_{1}^{n} U''_i(\sigma_0, T) \exp\left[-\frac{U''(\sigma_0, T)_i}{kT}\right],$$
(3)

$$U'_{i}(\sigma_{0},T) = U'_{0i} + \Delta U'(T) \pm \beta \sigma_{0}^{2}, U''_{i}(\sigma_{0},T) = U''_{0i} + \Delta U''(T) \pm \beta \sigma_{0}^{2},$$
(5)

$$\alpha = \frac{\gamma_{\sigma}^2 V_0}{6G}, \beta = \frac{\gamma_{\sigma}^2 V_0}{2K}, \tag{6}$$

where U'_{0i} , U''_{0i} is the activation energy of the formation and diffusion of the *i*th defect, respectively; σ_0 , σ_i is the hydrostatic stress and stress intensity; V_0 is the atomic volume; *k* is the Boltzmann constant; *h* is the Planck constant; *T* is the absolute temperature; *G*, *K* is the shear and bulk elasticity modules.

2.3 Thermodynamic analysis of interrelation between deformation and fracture

From the thermodynamic point of view, the process of plastic deformation and destruction is characterized by the competition of two opposite, interrelated and simultaneously occurring trends in the body element—the growth of the latent energy density u_e of various defects and damages arising and accumulating in the material due to the work of external forces ω_p , and its reduction (release) due to relaxation processes occurring inside the deformable body element; in this case, the first trend is associated with the deformation hardening and material damage, the second-with the dynamic return and dissipation of strain energy, causing the thermal effect q of plastic deformation.

A significant part of the dissipation energy q is not retained in the deformable element of the body, passes through it as if in transit and dissipates in the environment due to heat exchange \vec{q} . Only a small part of the dissipation energy q accumulates in the deformable element of the body in the form of a thermal component of the internal energy $\Delta u_T = q - \vec{q}$ increasing its temperature (self-heating effect).

In accordance with the law of conservation and transformation of energy

$$\omega_p = \Delta u_e + q \text{ and } \dot{\omega}_p = \dot{u}_e + \dot{q}.$$
 (7)

In the mechanics of a deformable solid, irreversible work ω_p and the power $\dot{\omega}_p$ of deformations are associated with the stress-strain state of the body element by the relation

$$d\omega_p = \sigma_i d\varepsilon_i^p, \, \dot{\omega}_p = \sigma_i \dot{\varepsilon}_i^p. \tag{8}$$

where $\dot{\varepsilon}_i^p$ is the rate of irreversible deformation.

Joint consideration Eqs. (7) and (8) allows to establish a unique relationship between the stress-strain and thermodynamic states of the body element

$$\dot{\varepsilon}_i^p = \frac{\dot{\omega}_p}{\sigma_t} = \frac{1}{\sigma_i} (\dot{u}_e + \dot{q}) = \dot{\varepsilon}_i^e + \dot{\varepsilon}_i^q.$$
(9)

Therefore, from the thermodynamic point of view, the total values of the work ω_p and irreversible deformation ε_i^p and the rates of their change $(\dot{\omega}_p, \dot{\varepsilon}_i^p)$ can be represented as the sum of two terms associated, respectively, with the deformation hardening and damage $(\dot{\varepsilon}_i^e = \dot{u}_e/\sigma_i)$ and dynamic return $(\dot{\varepsilon}_i^q = \dot{q}/\sigma_i)$ controlling quasi-viscous flow of the body element.

This important conclusion is of fundamental importance in the analysis of the relationship between the processes of deformation and destruction of the body element. For damage and destruction of the body element is responsible only part of the plastic (irreversible) deformation ε_i^e controlled by microscopic processes associated with deformation hardening and accumulation of latent energy of defects and damages. A significant part of the irreversible deformation ε_i^q controlled by relaxation (dissipative) processes does not affect the damage and destruction of the body element, but only causes its quasi-viscous flow (stationary creep). The relationship between the work and the degree of irreversible deformation and their components varies within a very wide range and depends on the structure of the material and the conditions of its deformation [1].

2.4 Thermodynamic condition of local fracture

The parameter of damage (scattered destruction) is taken as the density of the internal energy u accumulated in the deformable volumes, determined by the sum of two components: potential (latent) u_e and kinetic (thermal) u_T that is

$$\Delta u = \Delta u_e + \Delta u_T, \, \dot{u} = \dot{u}_e + \dot{u}_T. \tag{10}$$

This energy is associated with the accumulation in the deformable element of the body of static (Δu_e) and dynamic (Δu_T) damages and distortions of the crystal lattice, therefore, is dangerous, responsible for the scattered destruction (damage). The element of the body is considered to be destroyed if at least one local micro-volume responsible for the destruction, the density of internal energy reaches a critical (limit) value u_* corresponding to the loss of crystal lattice stability "in a large." This point corresponds to the appearance in the local micro-volume of a crack of critical size (according to Griffiths-Orovan-Irvin) and a sharp localization of the process at the mouth (top) of the crack. The thermodynamic condition of local fracture is written as

$$u(\bar{r}_{*},t_{*}) = u(\bar{r}_{*},0) + \int_{0}^{t_{*}} \dot{u}(\bar{r}_{*},t)dt = u_{*} = const.$$
(11)

here, $u(\bar{r}_*, 0)$ is the density of internal energy in the local micro-volume of the material in the initial (before deformation t = 0) state; $\dot{u}(\bar{r}_*, t)$ is the specific power of internal energy sources in the local volume responsible for the destruction; \bar{r}_* is the parameter characterizing the coordinates (x_*, y_*, z_*) of the local volume responsible for the fracture.

2.5 Thermodynamic criterion of fracture

In accordance with the structural-energy analogy of the process of mechanical destruction and melting of metals and alloys [5] and theoretical and experimental

studies [1, 6], the critical value of the internal energy density u_* in the local macro-volume of the material responsible for destruction coincides well with the known thermodynamic characteristic of the material ΔH_S is the enthalpy of melting, that is.,

$$u_* = \Delta H_s = \int_0^{T_s} c_p dT + L_s. \tag{12}$$

here, T_S is the melting temperature; c_p is the heat capacity; L_S is the latent heat of melting.

3. Triboergodynamic's method

3.1 Friction

3.1.1 Initial or zero axiom of friction

The present day analysis of sum total of modern friction investigations may be presented in the form of three theses (others are also possible) of essential property which are shared by many research workers as undoubt proof as to the most characteristic properties of generalized friction model:

- Friction is the phenomenon of resistance to the relative movement (movement) of surfaces, localized at the points of contact tangent to them;
- Friction is the process of converting (transforming) the energy of external mechanical motion into other types of energy, and mainly into thermal energy;
- 3. Friction is a process of elastic-plastic deformation and fracture localized in thin surface layers of friction pair materials.

These three axioms may be regarded as initial friction axioms and called "zero" friction axioms as the starting-point of whence it is possible to develop logical analysis of generalized engineering property for friction process.

In the capacity of axiomatic method of friction investigation of initial friction axioms [4] mentioned above the author thinks it expedient to use the method of ergodynamics of deformable solids [1–3] which are at present may be taken as axiomatic, that is, method which may be trusted owing to the theoretical, experimental and practical substantiation.

3.1.2 Balanced and unitary attributes of friction

Taking into consideration that basic attribute of any system is a balance attribute then tribosystem framework should be determined by the framework of obeying, for example, energy balance friction. Then it follows that basic equation for tribosystem is an energy balance equation characterizing movement within friction system in a generalized and quantitative way. Constituent parts of this balance must determine basic quantitative regulations of energy transformations (and movement) within the system.

Friction, Lubrication and Wear

Thus, tribosystem in the most generalized sense is quantitatively characterized by the energy balance equation. Most generalized quantitative regulatities of tribosystem behavior (states) are determined by magnitudes relations among constituencies of friction energy balance. These conditions may also be taken as friction axioms. In accordance with that it is possible to show justice of entropy balance equation and so of information and etc.

Taking into consideration the fact that the most characteristic magnitude of the most global balance principle is unit (whole), then, consequently, the basic parameters of tribosystem (friction), expressed as indexes of relations among balance constituents must also have criterion (limit) magnitudes equal to unit.

3.1.3 Common energy analysis of friction process

In the most general case the work of friction process W_F is summed up from the work of elastic W_F^{elast} and plastic W_F^{plast} deformation and wear (failure) of contact volumes (**Figure 2**) and work for overcoming forces of viscous friction and failure of lubricant material W_{lub} :

$$W_F = W_F^{elast} + W_F^{plast} + W_{lubr}, \tag{13}$$

For particular case of friction without lubrication ($W_{\text{lub}} \cong 0$) and in the conditions of stationary (developed) friction, when the work of elastic deformation may be neglected due to their insignificance, friction work W_F will be determined mainly by the work of plastic deformation of surfaces (contact volumes) of shaft W_{F1}^{plast} and of bearing W_{F2}^{plast} :

$$W_F = W_F^{plast} = W_{F1}^{plast} + W_{F2}^{plast}.$$
 (14)

3.2 Structural-energy interpretation of friction process

It is known friction is characterized a product of frictional forces *F* by friction distance ℓ , that is., the work ω_f , expended on overcoming frictional forces



here, $\dot{\omega}_f = d\omega_f/dt$ is a power of friction dissipation of energy; $\dot{u}_e = du_e/dt$ is the rate of storing latent energy in deformed (contact) volumes; $\dot{q} = dq/dt$ the power of thermal effect of plastic deformation (friction).

Since the contact volumes of both materials that make up the friction pair are deformed by friction (see **Figure 2**), Eqs. (16) and (17) should be written as

$$\omega_f = \Delta u_{e1} + \Delta u_{e2} + q_1 + q_2, \tag{18}$$

$$\dot{\omega}_f = \dot{u}_{e1} + \dot{u}_{e2} + \dot{q}_1 + \dot{q}_2. \tag{19}$$

These equations show, that from thermodynamic point of view, the work ω_f of friction forces, (friction power $\dot{\omega}_f$) is related to plastic deformation of the contact volumes. The work ω_f may be divided conventionally into two specific parts.

The first part of the friction work is related to the change in the deformable (contact) volumes of materials of latent (potential) energy Δu_{e1} and Δu_{e2} . It is the energy of various elementary defects and damages arising and accumulating in deformable volumes. This energy is a unique and integral characteristic of submicroand microstructural changes that occur in plastically deformable volumes of materials [1, 2, 7]. It is a measure of deformation hardening and damage of materials.

The second part of the friction work ω_f is related to the processes of dynamic return, accompanied by the release of latent energy and the thermal effect q_1 , q_2 of friction. This energy is associated with the movement and destruction of various elementary defects of opposite signs, their exit to the surface, healing reversible submicroscopic discontinuities, etc.

The relations between the components of the energy balance of the friction process Δu_{e1} and Δu_{e2} , as well as q_1 and q_2 vary widely and are determined by the physical and chemical properties of the materials that make up the friction pair, their structure and the conditions of the friction process.

In the most general case, Eqs. (18) and (19) should be presented (**Figure 2**) taking into account the real (not unit) sizes of the tribocontacts.

$$W_f = \Delta U_e + Q = \Delta U_{e_1} + \Delta U_{e_2} + Q_1 + Q_2, \tag{20}$$

$$\dot{W}_f = \dot{U}_e + \dot{Q} = \dot{U}_{e_1} + \dot{U}_{e_2} + \dot{Q}_1 + \dot{Q}_2,$$
 (21)

where $\Delta U_e = V_f \Delta u_e$; $\dot{U}_e = V_f \dot{u}_e$; V_f is contact (deformed) volume of the materials of the friction pair.

Solving Eqs. (20) and (21) with respect to the friction force F, we obtain generalized equations for the friction force

$$F_{l} = \frac{\Delta U_{e_{1}} + \Delta U_{e_{2}}}{l} + \frac{Q_{1} + Q_{2}}{l}.$$
 (22)

$$F_{v} = \frac{\dot{U}_{e_{1}} + \dot{U}_{e_{2}}}{v} + \frac{\dot{Q}_{1} + \dot{Q}_{2}}{v},$$
(23)

where l and v are the friction path and the slip velocity.

Dividing both parts of the Eqs. (22) and (23) by the normal force *N*, we present generalized equations for the coefficient of friction

$$\mu_{l} = \frac{\Delta U_{e_{1}} + \Delta U_{e_{2}}}{Nl} + \frac{Q_{1} + Q_{2}}{Nl},$$

$$\mu_{v} = \frac{\dot{U}_{e_{1}} + \dot{U}_{e_{2}}}{Nv} + \frac{\dot{Q}_{1} + \dot{Q}_{2}}{Nv}.$$
(24)
(25)

Thus, friction is generally described by the equation of energy balance and from the thermodynamic point of view [1–4] it is a competitive process of two (mentioned above) opposite, interrelated and simultaneously occurring in the deformable contacts trends. According to the energy balance scheme (**Figure 1**) for plastic deformation and fracture [1] presented above (relationships $\Delta u = \Delta u_e + \Delta u_T$ and $q = \Delta u_T + \vec{q}$), equations [8] for friction work W_f , frictional force *F* and friction coefficient μ (without lubrication) has view

$$W_f = \Delta U_e + Q = \Delta U_{e_1} + \Delta U_{e_2} + \Delta U_{T_1} + \Delta U_{T_2} + \dot{Q}_1 + \dot{Q}_2,$$
(26)

$$\dot{W}_f = \dot{U}_e + \dot{Q} = \dot{U}_{e_1} + \dot{U}_{e_2} + \dot{U}_{T_1} + \dot{U}_{T_2} + \vec{Q}_1 + \vec{Q}_2,$$
 (27)

$$F_{l} = \frac{\Delta U_{e}}{l} + \frac{Q}{l} = \frac{\Delta U_{e_{1}} + \Delta U_{e_{2}}}{l} + \frac{Q_{1} + Q_{2}}{l},$$
(28)

$$F_{v} = \frac{\dot{U}_{e_{1}} + \dot{U}_{e_{2}}}{v} + \frac{\dot{Q}_{1} + \dot{Q}_{2}}{v} = F_{mechanical} + F_{molecular},$$
 (29)

$$\mu_{l} = \frac{\Delta U_{e_{1}} + \Delta U_{e_{2}}}{Nl} + \frac{Q_{1} + Q_{2}}{Nl} = \mu_{adapt} + \mu_{dis} = \mu_{adapt} + \mu_{T(dis)} + \mu_{\vec{Q}(dis)}, \quad (30)$$

$$\mu_{v} = \frac{\dot{U}_{e_1} + \dot{U}_{e_2}}{Nv} + \frac{\dot{Q}_1 + \dot{Q}_2}{Nv} = \mu_{deformation} + \mu_{adhesion}, \tag{31}$$

where $\Delta U_e = V_f \Delta u_e$; $Q = V_f q$; $\vec{Q} = V_f \vec{q}$; $\dot{U}_e = V_f \dot{u}_e$; $\dot{u}_e = d u_e/d t$ is the rate of latent energy density change in the contact volumes; V_f is a deformable volume of friction; μ is the coefficient of friction; μ_{adapt} is the adaptive coefficient of friction; $\mu_{T(dis)}$ and $\mu_{\vec{Q}(dis)}$ are the static and dynamic components of dissipative coefficient of friction; ΔU_T is the thermal component of internal energy; N is the normal load; l is the friction distance; v is the sliding velocity. The latent energy density Δu_e is an integral parameter of tribostate and damageability (failure (Δu_e^*)) of solids [1].

Thus, viewed thermodynamically, the work done by friction forces W_f (the friction power \dot{W}_f), the friction force F and the friction coefficient μ may be



Figure 1. Scheme of the energy balance for the plastic deformation (friction) of a solid [1-3].

classified conventionally into two specific components with different kinetic behavior [3, 9]. The first component is associated with microscopic mechanisms of adaptive type and relates to the change of latent (potential) energy ($\Delta u_{e_1}, \Delta u_{e_2}$) of various elementary defects and damages that are generated and accumulate in the deformable volumes of materials friction pair (**Figure 1**). This energy is a unique and integral characteristic of the submicro- and microstructural transformations that occur in plastically strained materials [1–3, 9]. It is a measure of deformation hardening and damage of materials. The second component is associated with microscopic mechanisms of dissipative type and related to dynamic recovery processes in which latent energy is released and heat effect of friction (q_1, q_2) take place. This energy is associated with the movement and destruction of various elementary defects of opposite signs, their exit to the surface, healing reversible submicroscopic discontinuities, etc. The ratios of the components Δu_{e_1} and Δu_{e_2} as well as q_1, q_2 of the balance vary over a wide range, depending on the physical, chemical, and structural properties of the materials that comprise the friction couple and the friction process conditions [8].

Thus, the thermodynamic analysis of the plastic deformation and fracture of the solid volume at friction allows us to obtain generalized (two-term) dependences for the friction force F and the friction coefficient μ , which corresponds to the modern concepts of the dual nature of friction [10, 11]. It is a molecular mechanical Eq. (29) and deformation-adhesion Eq. (31) theories of friction. But, more correctly it is necessary to speak about adaptive-dissipative nature (model) of friction Eq. (30).

As follows from the equations of the energy balance of friction Eqs. (26) and (27), the whole variety of manifestations of friction and wear can be conditionally reduced to at least two fundamentally different states. The first condition determines all types of damageability and wear, the second-the so-called condition of "wearlessness" [7].

The state of damageability and wear is characterized by the components of energy balance Eqs. (26) and (27), which are responsible for accumulation of internal energy $\Delta u = \Delta u_{e1} + \Delta u_{e2} + \Delta u_{T1} + \Delta u_{T2}$ in deformed volumes, that is, the process is irreversible [4, 8]. The "wearlessness" state is characterized by the components of the energy balance Eqs. (26) and (27), which are responsible for the dynamic dissipation (reversibility) of strain energy into elastic and structural dissipated energy $\vec{q} = \vec{q}_1 + \vec{q}_2$ of friction contact [4, 8].

In its turn, the first state may be classified depending on the relation between potential Δu_e and kinetic Δu_T components of internal energy. It is subdivided conventionally into mechanical damage and wear (due to so-called structure activation) and thermal damage and wear (due to thermal activation). For instance, let the thermal component of internal energy Δu_T be equal to zero ($\Delta u_T = 0$) and the internal energy variation at damage and wear be defined only by variation of the potential $\Delta u_e (\Delta u = \Delta u_e)$ component. Then, the mechanical damage and wear with brittle fracture of surfaces take place. On the contrary, if we have $\Delta u_e = 0$ ($\Delta u = \Delta u_T$), then the thermal damage and wear with ductile fracture of surfaces take place. All the intermediate values of the components are associated with quasibrittle or quasi-ductile fracture of solids [4, 8].

In the most general case, taking into account a fundamental tribology's notion of the "third body" [10], the energy balance at dry friction Eq. (20) should be written as

$$W_f = \Delta U_{e1} + \Delta U_{e2} + \Delta U_{e3} + Q_1 + Q_2 + Q_3.$$
(32)

In the special case, where the friction is localized into volume of the "third body" (**Figure 2**) Eq. (32) develops into

$$W_f = \Delta U_{e3} + Q_3. \tag{33}$$

here, $\Delta U_{e3} = V_3 \Delta u_{e3}$.

3.3 Energy interpretation of the friction coefficient by Amonton (Leonardo da Vinci)

According to the main conclusion of the thermodynamic theory of strength [1], as a structural parameter should not take the entire value of the accumulated plastic deformation, but only its part associated with the deformation hardening, which is uniquely and integrally determined by the density of the potential component of the internal energy (i.e., the density Δu_e of the so-called latent energy) of various defects and damages accumulated in the plastically deformable volumes of the material. With this in mind, if we neglect the heat effect *Q* of friction, one will infer from the thermodynamic analysis of friction of Eqs. (24) and (25) that the Amonton (Leonardo da Vinci) friction coefficient is

$$\mu = \frac{\Delta U_e}{\mu^* N l} = \frac{F}{N}; F = \frac{\Delta U_e}{l}; Q \cong 0, \mu^* = 1.$$
(34)

Consequently, the coefficient of friction has a very deep physical sense. On the one hand, it is the parameter which generally characterizes the resistance of relative displacement (movement) of surfaces, for it reflects the portion of energy, which "is done by friction away" as accumulated latent energy ΔU_e , by relation to parameter of external forces work $\mu * Nl$ (energy of external relative movement) [12]. On the other hand, it is the generalized characteristic of damage, for it is defined of the latent energy density Δu_e as integral characteristic of the structure defectiveness measure, because this energy is the generalized parameter of damage. Here too, coefficient of friction generally reflects the structural order (disorder) of deforming contact volume, since the parameter $\Delta U_e = \Delta u_e V_f$ is defined of the energy of defects and damages of different types, that are accumulated into contact volumes V_f solids [12].

Thus, the coefficient of friction is a true and generalized parameter of the state of the tribosystem. It follows a very important conclusion that the analysis of the regularities of the evolution of the states of tribosystems is, first of all, the analysis



Figure 2. *Conditional scheme of friction contact* [4].

of the laws of change of the accumulated latent energy of deformation by the contacting volumes of the solid, that is, change of Amontons coefficient of friction [12].

3.4 Generalized experimental friction curves

The dependences obtained for the friction coefficient μ are in agreement with experimental curves $\mu = \mu(N, v)$ (**Figures 3–5**). Analyzing various experimental friction curves using the Eqs. (20)–(31) of friction energy balance, it was concluded



Figure 4.

Generalized friction experiments in I.V. Kragelsky's interpretation [10]: sliding velocity (load: 1—small; 2 and 3—medium; 4—considerable).



Figure 5. *Experimental results of Watanabe for a pair of friction—nylon 6—steel* [14].



Figure 6. Structural-energy diagram of the evolution of friction surfaces [4, 16–18].

[4] that the experimental friction curves (**Figures 3–5**) of the type a $\mu = \mu(N, v)$ are generalized experimental friction curves and reflect the general (for all materials and friction pairs) laws of evolution (changes in the friction coefficient) of tribosystems.

3.5 Structural-energy regularities of rubbing surfaces evolution

An analysis of modern experimental data using Eqs. (20)–(31) has shown that the experimental friction curves of type $\mu = \mu(N, v)$ are the generalized

experimental friction curves that reflect the evolution (the change in the friction coefficient) of tribosystem.

We propose an energetic interpretation of the experimental friction curves $\mu = \mu(N, v)$ (**Figure 6**). According to our concept [4, 15, 16], the ascending portion of the friction coefficient curve μ is mainly controlled by processes associated with the accumulation of latent energy ΔU_e in various structural defects and damages. Here the increase in μ is due to the increasing density of latent (potential) energy Δu_e and the increasing adaptive friction volume V_f . The descending portion of the friction curve is mainly controlled by processes associated with the release and dissipation of energy $Q = \Delta U_T + \vec{Q}$. Here the decrease in μ is due to the decrease in latent energy density within the friction volume V_f or (which is virtually the same) to the decrease of the adaptive friction volume V_{adapt} ($u_e = u_e^*$) and to the increase of the dissipative volume V_{dis} ($\vec{q}^* = u_e^*$).

The evolution of the tribosystem is presented in the form of a diagram (**Figure 6**) and has an adaptive-dissipative character Eqs. (29)–(34) and reflects the competitive (dialectical) nature of friction. The evolutionary curve has a number of fundamental points (1–5) of transition states of the tribosystem, which are strictly subject to the balance principle of friction. Between these points there are the most characteristic areas of behavior of the tribosystem. These areas reflect the most general properties of nonlinear dynamics of friction evolution.

So, in **Figure 6** you can see the following conditionally marked points and areas: 0-1—the area of static friction and strain hardening; 1—the point of the limit strain hardening; 1-2—excess energy pumping area; 2—point of adhesion (seizure) and transition of external friction into internal (point of critical instability); area of formation of dissipative structures (formation of temperature fluctuation in the friction volume); 3—the point of minimum compatibility (maximum frictionness); 1-2-3—area of self-organization; 3-4—compatibility area; 4—point of wearlessness (abnormally low friction); 5—thermal adhesion point.

The ideal evolution of the friction contact is symmetric. The friction process begins and ends in areas of elastic behavior. Between them is the plastic maximum (super activated state) as a condition of self-organization and adaptation. In the most general case, the regularities of evolution (adaptation) of tribosystems can be represented as two-stage (**Figure 6**). At the first stage (0–2) of the evolution of the friction contact, it tends to form a critical volume V_f^* of friction (point 2). This is the smallest volume of friction that has accumulated the maximum potential energy of structure defects. This is an elementary tribosystem, that is., an elementary and self-sufficient energy transformer. In the first stage, the latent energy density Δu_e increases to a limit value Δu_e^* within the critical friction volume V_f^* .

The volume of friction V_f^* is constant in the second stage of evolution. At this stage, contact is evolutionarily developed due to structural transformation. At this stage, a wide spectrum of compatible friction structures (**Figure 6**) can be formed depending on the nature of the environment. The second stage (2–4) can be considered as a structural transformation of the critical friction volume V_f^* (elementary tribosystem) conditionally to the adaptive V_{adapt} and dissipative V_{dis} friction volumes (**Figure 7**). The end point (point 4) of this stage of evolution is characterized by the complete transformation of the critical adaptive friction volume V_{adapt}^* into the dissipative V_{dis}^* one.

The above volumes mentioned characterize different regularities of energy conversion of external mechanical motion at friction. Adaptive volume V_{adapt}



Figure 7.

The model of the energy evolution of the contact friction volume at points 1-5 of the diagram (Figure 6) [4].

is associated with irreversible absorption of strain energy. In this volume, there is an accumulation of latent deformation energy Δu_e and centers of destruction are born. The dissipative volume V_{dis} is able to reversibly transform (dissipate) the energy of the outer movements. In this volume, there is no accumulation of latent deformation energy due to the flow of reversible elastic-viscoplastic deformation.

Theoretical and calculated estimates [4, 16, 18] have shown that the dissipative friction volume performs a reversible elastic transformation of the energy of external mechanical motion with a density \vec{q}^* equal to the critical density u_e^* of the latent energy.

The culmination of the evolution of the tribosystem is its final and limiting state of point 4—the state of abnormally low friction and wearlessness (maximum efficient).

A schematic evolution of the contact volume of friction in diagram's points 1–5 is presented in **Figure 7**.

Calculations show [4] that with the ideal evolution of the tribosystem, the adaptive (Amonton) coefficient of friction μ_{adapt} at point 2 of the diagram drops sharply, reaching at point 4 the elastic coefficient of friction μ_{elast} . For point 4 of compatibility area 3-4, an equation of energy balance Eq. (30) should be put in the following way:

$$\mu_{adapt} = \mu^* - \mu_{dis} = 1 - \mu_{dis} = \mu_{plast} = 0 = \mu_{elast}; \mu^* = 1, 0.$$
(35)

Thus, we have at point 4 of the ideal evolution of the contact friction volume the condition of perfectly elastic-viscous-plastic deformation. This actually shows the Eq. (35), that is, the coefficient of friction of Amonton μ_{adapt} , being, in fact, a plastic coefficient of friction μ_{plast} has a minimum value equal to zero. Consequently, plastic friction becomes elastic with the coefficient μ_{elast} of friction. This means that the plastic deformation of the contact friction volume is realized with the maximum

dynamic dissipation (\overline{Q} = max) of the accumulated latent energy. Therefore, the amount of accumulated energy at point 4 is zero ($\Delta U_e = 0$). This fact proves the ideal state with the full evolution of the contact volume. From the physical point of view, this state can be explained by the complete dissipating of the energy ΔU_e^* accumulated at point 2, along the newly formed structures of point 4 in the form of

elastic energy of interaction between them (energy \vec{Q} of dynamic dissipation). Here $\mu_{dis} = 1$, 0. The structural elements themselves are defectlessness— $\mu_{adapt} = 0$, and friction is elastic— $\mu = \mu_{elast}$.

It is shown [4] that the value of the minimum adaptive friction volume V_{adapt}^{\min} corresponding to the zero value of the plastic friction component μ_{adapt} is not zero, but is equal to the size of a certain minimum structural element of the deformable solid.

3.6 The idea of a mechanical (nano) quantum of dissipative friction structures

The result of ideal elementary tribosystem (contact) evolution is forming of unique nanostructure—a mechanical (nano) quantum. Strict ideas about mechanical quantum obtained [4, 18] considering for point 4 of the friction evolution diagram the equation of a quasi-ideal solid:

$$\vec{Q}^* = \vec{S}_Q T = \mu_{dis}^* N l_f = V_f^* u_e^* = V_f^* \vec{q}_*.$$
 (36)

This equation is a special case of the solution of the equations of energy balance of friction Eq. (29), at $\mu_{adapt} = 0$ and $\mu_{dis} = 1 = \mu_{dis}^*$. Here S_Q is the inertial entropy of compatible friction volume; *T* is the characteristic temperature of compatible contact friction volume; l_f is the linear dimension of elementary contact.

Accordingly, under the conditions of maximum compatibility (point 4), when the tribosystem implements a complete evolutionary cycle of adaptation with the formation of the most perfect, dissipative structure, its (structure) behavior is subject to the equation of state of a quasi-ideal solid, that is, it should be assumed that the interactions between the elements of this structure are minimized—the state of ideal elasticity in dynamics. Eq. (28), taking into account the Planck-Boltzmann formula $S = k \ln W$ and the real number of atomic oscillators N_f in the volume of the elementary tribosystem (contact) V_f^* , is given to the form explaining the regularities of friction in terms of the evolution of systems:

$$\mu_{\rm diss} = \frac{\vec{S_Q}}{Nl_f} = \frac{kTN_f \ln W}{Nl_f},\tag{37}$$

$$\mu_{adapt} = 1 - \mu_{diss} = 1 - \frac{kTN_f \ln W}{Nl_f} = 1 - \frac{S_Q T}{Nl_f} = \frac{S_U T}{Nl_f},$$
(38)

where k is the Boltzmann constant; W is the probability of state; S_U is the configuration entropy of friction (contact) volume.

The tribosystem always tends to some optimal state characterized, that is, to the most probable state $W' = N_f \ln W$ for the given friction conditions.

The analysis and solution of these equations [4, 16–18] allows to show the principle of the constancy of the magnitude of the probability (the state's parameter (order)) *W* of the tribological system) for the entire range of compatible friction, namely $\ln W = 3$, and $W = e^3 = 20$, 08553696....

The number of thermodynamic state probability *W* equal to 20, 08553696... was interpreted [4, 12–15] as the smallest number of linear, atomic oscillators in one of the three directions of the minimum adaptive friction volume V_{adapt}^{min} corresponding to the state of almost absolute elastic friction—abnormally low friction (safe deformation threshold). Accordingly, the number of atomic oscillators in this volume is $V_Q = (e^3)^3 = (20, 08553695...)^3 = 8103, 083969....$ It is the universal size (volume) of mechanical quantum [4, 7, 16–18].

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On the other hand, taking the meaning of Boltzmann entropy S, we obtain a universal friction constant $R_f = kN_f$ [4, 16–18], which in physical sense characterizes the "energy size" of the elementary tribosystem (TS) containing under ideal conditions the same number of atomic oscillators N_f (mechanical quanta N_Q):

$$R_f = k \cdot N_f = k \cdot W^3 \cdot N_Q = R_{MQ} \cdot N_Q, \frac{J}{grade \cdot TS},$$
(39)

$$R_{MQ} = k \cdot W^3, \frac{J}{grade \cdot MQ}, \tag{40}$$

where R_{MQ} is the universal constant of deformation at friction.

As follows from the calculations [4], the size of the minimum adaptive friction volume V_{adapt}^{\min} coincides in its magnitude with the size of the submicroscopic zone at the mouth of the crack, which for metals is equal $(4...9) \cdot 10^{-6}$ mm, that is, with the size of the critical volume responsible for the fracture. Thus, the size of the minimum adaptive friction volume $V_{adapt}^{\min} = V_{elast}$ can be represented as the size of some mechanical "quantum".

This mechanical quantum is the minimum number of atoms capable of providing a configuration of their distribution (structure), which has the property of reversibly absorb and dissipate (return) the energy of external mechanical motion (action). It also represents the smallest structural formation under plastic deformation and is formed during the transition of the tribosystem (deformable volume) through the extremely activated (critical) state (**Figure 6**) due to the development of self-organizational processes of adaptation of the tribosystem. The mutual rotational-oscillatory motion of these mechanical quanta relative to each other inside the elementary tribosystem (contact) determines the state of the most perfect dissipative structure of friction. Actually, this state is described by the equation of state of a quasi-ideal solid Eq. (36), the state when the interaction between the elements of the structure (mechanical quanta) is minimized-the state of the ideal elasticity of the quasi-viscous flow. The calculated coefficient of friction between the quanta is approximately 10^{-8} [4, 16–18].

The conclusion that the mechanical quantum is the smallest structural formation under plastic deformation (friction) is confirmed by the calculation. If we compare the values of the elastic modules E to the atomic (true) elasticity E_r , we obtain values equal to 60, where the number 60 = 3W can be interpreted as a characteristic of the volume elasticity of one mechanical quantum—the minimum adaptive friction volume V_{adapt}^{min} . Calculation of the parameter $W \cong 20 = E/3E_r$ for different metals and steels gives an average value of 20, 77 (**Table 1**); $\Delta H_S = 3E_r$ is the enthalpy of melting.

It is concluded [4, 16–18] that for all materials, under the conditions of the ideal evolution of the tribosystem, the number of atoms N_f (mechanical quanta (MQ)) in the volume of one elementary tribosystem (TS) is constant. Thus, we can talk about the amount of matter equal in mass to one elementary tribosystem and to one mechanical quantum.

3.7 The synergy of the tribosystem and the optimality states

Mechanical quantum is a dynamic oscillator of dissipative friction structures. The ideal, quasi-elastic state of contact at its full evolution is the effect of the most complete energy dissipation of external mechanical motion on the

Metals and steels	$E imes 10^{-3}$, MPa	$ig(\pmb{u}_e^{*}ig) \Delta \pmb{H_S} imes \mathbf{10^{-3}},\mathbf{MJ/m^3}$	$E/3E_r$
Cr	235.4	8.5	27.69
Mg	44.4	1.9	23.37
Ag	79.0	3.7	21.35
Au	78.7	4.0	19.67
Со	200.1	10.6	18.88
Fe	211.4	9.9	21.35
Ta	184.4	10.6	17.39
Ti	105.9	6.7	15.8
Nb	104.0	9.2	11.3
Zr	95.6	5.7	16.77
Мо	316.9	12.0	26.4
W	392.4	14.4	27.25
Ni	201.1	9.4	21.39
Iron	210.9	10.1	20.88
20	200.1	9.5	21.06
1Kh13	206.0	8.9	23.14
3Kh13	218.8	9.2	23.78
Kh18N9T	199.1	9.4	21.19
Kh18M9	199.1	9.6	20.74
30Kh	214.1	10.2	20.99
30N3	207.5	10.3	20.11
40	209.4	9.7	21.58
30G2	207.2	10.0	20.72
30KhGN3	208.0	10.2	20.4
G13	204.0	10.0	20.4
50S2G	196.2	10.3	19.05
U8	198.0	10.3	19.22
U12	198.0	10.4	19.04

Table 1.

Parameter estimation for different metals and steels [4].

newly formed (on the mechanism of self-organization in the vicinity of the critical state) structural elements-mechanical quanta (dynamic oscillators), which implement the most complete rotational-oscillatory behavior relative to each other in the volume of the elementary tribosystem. At the same time, the resistance to their relative interaction is minimal-elastic and corresponds to the elasticity of ideal atomic (thermodynamically equilibrium) interactions at the level of electronic shells.

The universal constants of the mechanical quantum and the elementary tribosystem (material point) determine both the quantum model of surface damping:

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$$\mu_{dis} = \frac{3R_{MQ}Tn_i}{Nl_f} = \frac{U_{1Q}n_i}{U_{1Q}n_*} = \frac{n_i}{n_*} = 1 - \mu_{adapt}; \quad \mu_{adapt} = 1 - \frac{n_i}{n_*} = \frac{n_{dest}}{n_*}, \quad (41)$$

taking into account the quanta of destruction n_{dest} (irreversible component of the process) and the quanta of damping n_i (reversible, elastic component (fatigue number)), and the probabilistic model of the evolution of the tribosystem to the most ordered state:

$$\mu_{adapt} = 1 - \mu_{dis} = 1 - \frac{R_f T \ln W_i}{Nl_f} = 1 - \frac{\ln W_i}{\ln W_*}.$$
(42)

where $3R_{MQ}T = U_{1Q}$ is the energy of one mechanical quantum; W_i and W_* is the current and limit probabilities of states of compatible tribosystems.

According to the model of quantum damping of surfaces under friction in the conditions of the most complete evolution (adaptation) of the elementary tribosystem, all mechanical quanta except one, elastically and reversibly transform the energy of external action (mechanical motion). One mechanical quantum of radiation (\cong 8103 atoms)—there is a minimum loss (the essence of wearlessness (the ideal damping properties) or the standard of wear).

The linear size of a mechanical quantum is equal to the diameter of a spherical ideal crystal with atomic roughness [4, 7]:

$$D_{MQ} = 2 \cdot W \cdot \overline{d}_a \cdot (3/4 \cdot \pi)^{1/3} = 7,177nm.$$
(43)

here, \overline{d}_a is the average atomic diameter, for metals; $W = e^3$ is the mechanical quantum state parameter [4].

The mechanical quantum (**Figure 8**) itself should be considered as an elementary nanostructure of a metal solid.



Figure 8. Model of an ideal crystal of elementary nanostructure of friction contact (8103 atomic cubical cells) [4, 16–18].

Calculations have shown [4, 8] the number N_Q of such mechanical "quanta" (subtribosystems) within the elementary tribosystem's volume $V_f^* = V_{dis}^*$ to be $0.63 \cdot 10^8$ which is close to the safe number n_* of fatigue cycles.

Therefore, the smaller the coefficient of friction μ_{adapt} (the greater the coefficient μ_{dis}) of the tribosystem, the higher its fatigue endurance (durability), as a greater number of mechanical quanta involved in the process of damping (elastic return) of the energy of the external mechanical motion (impact), and consequently the smaller the number of quanta associated with the fracture (accumulation of latent energy of defects and damage of the limit value). In the limit, the tribosystem is characterized by the effect of "wearlessness" (abnormally low friction), corresponding to the state of almost complete thermodynamic reversibility of the friction (deformation) process. Here, all mechanical quanta, with the exception of one, reversible elastic transform (damp out) the energy of external mechanical movement. By analogy with classical quantum theory, we can say that in this case the system (tribosystem) is in the ground state (here, as if all mechanical quanta are directed against the field)-tribosystem cannot give energy to any other system (environment) simply because it (tribosystem) and does not accumulate energy in this state. In this case, the tribosystem is in almost perfect balance with the environment.

The principle of mechanical quantum determines nanoquantum levels of all friction parameters of compatible (optimal) tribosystems and other.

4. The model for the evaluation of wear of compatible friction

The model [4] of the moving critical (equilibrium) friction volume (**Figure 9**) is considered for the analysis of wear problems.

Here, the instantaneous value of the friction work W_{f_i} is connected with the friction work \dot{W}_f per unit time, taking into account the uniform distribution of contacts (micro-shocks) in the longitudinal n_v and transverse n_n directions of the friction surface:



Figure 9. Scheme to the calculation of wear parameters of friction [4].

Accordingly, we have a number of ratios for power, force and coefficient of friction

$$\dot{W}_{f}^{*} = \dot{W}_{f_{i}}^{*} \cdot n = V_{f}^{*} \cdot \Delta u_{e}^{*} \cdot n = V_{f_{H}}^{*} \cdot \Delta u_{e}^{*} \cdot n_{v}, \qquad (45)$$

$$F^* = \frac{\dot{W}_f^*}{v} = \frac{V_f^* \cdot \Delta u_e^* \cdot n}{l_f \cdot n_v} = \frac{V_{f_H}^* \cdot \Delta u_e^*}{l_f},$$
(46)

$$\mu^{*} = \frac{\dot{W}_{T}^{*}}{N^{*} \cdot v} = \frac{V_{f}^{*} \cdot \Delta u_{e}^{*} \cdot n}{N^{*} \cdot v} = \frac{V_{f_{H}}^{*} \cdot \Delta u_{e}^{*}}{N^{*} \cdot v}.$$
(47)

Here $V_{f_H}^* = V_f^* \cdot n_H$ (**Figure 9**); W_T^{i*} is the instantaneous (contact) the value of the friction work; $n = \frac{V_f^t}{V_f} = n_v \cdot n_H$ is the ratio of the volume of friction V_f^t deformable per unit time *t* to the instantaneous volume of friction V_f ; n_v , n_H is the number of micro-shocks in the sliding direction of the sample per unit time and in the transverse direction.

Eq. (47), performed to the form of the $\mu^* = \frac{h_r \cdot \Delta u_e^*}{p_r \cdot l_f} = \frac{h_a \cdot \Delta u_e^*}{p_a \cdot B}$, represents the basic equation of wear for compatible friction region:

$$\tau_r = \frac{h_r}{l_f} \Delta u_e^* = I_r \Delta u_e^*, \qquad (48)$$

$$\tau_a = \frac{h_a}{B} \Delta u_e^* = I_a \Delta u_e^*.$$
(49)

here, I_r , I_a is the linear wear rate, related to the real and nominal areas of contact; B, H is the sample sizes in the slide and the longitudinal directions.

5. Nano quantum models of the maximum capacity for work of the tribosystem

5.1 The principle of calculating the wear of gears

All parameters of compatible (optimal) friction should be in nanoquant levels, which are commensurate with the parameters of one mechanical quantum standard of wear.

Operation of all heavily loaded tribosystems should be considered from the standpoint of the ideal evolution of tribosystems. This is a perfect condition contact friction is the true indicator of the state of the tribosystem for practical examples of tribology. This is the standard of maximum efficiency of the tribosystem—abnormally low friction and wearlessness.

A typical example of wear (destruction) of real tribosystems on the model of mechanical quantum is the work of gears (for example, reducers) and systems of wheel-rail and other, in which the elementary particle of wear (pitting) is wear equal to one mechanical quantum. Imagine the engagement of a pair of teeth involute profile on the field of the length of the active line of engagement (**Figure 10**) as the model of smooth surfaces with uniformly distributed equilibrium roughnesses after run-in (elementary tribosystems, which are analogues of the material point of mechanics). Engagement of a pair of teeth corresponds to the theoretical principle of running two cylinders under the conditions of Hertz elastic-plastic contact. The materials of the teeth work at the limit of the fatigue threshold, which corresponds to the minimum loss (pitting) of the contact volume (elementary tribosystem) in the form of a single mechanical quantum.





When working gear engagement, for each revolution of the wheel (gear), each roughness (material point) of the active surface of the tooth is loaded once, with a minimum loss (wear) in one mechanical (nano) quantum. Since the critical volume of friction (elementary tribosystem) contains $0.63 \cdot 10^8$ mechanical quantum, the number of loads (wheel revolutions), equal to the critical number of loading cycles —63 millions, leads to fatigue wear (loss) of the material layer of unit thickness h_* . Linear wear h_* of the gear wheel is equal to the diameter $Q_{TS} = 2.85 \cdot 10^{-6}$ m of the equilibrium friction volume V_f^* (**Figure 10**) [19]. This is a physical criterion of wear. Accordingly, it is clear that the constructive limit criterion of wear of the tooth of the gear is equal to the limit of wear when the bending strength of the tooth is violated. For example, this is approximately 0.3 modulus of the tooth of the gear.

Consequently, the elementary nanostructure of deformable solids should be considered as the wear standard and used to optimize the operating time of real highly loaded Hertzian friction systems.

5.2 Evaluation of the capacity for work of bearings of internal combustion engines

Let's take an engine with an average shaft rotation— $n = 1500 \text{ min}^{-1}$. Take the limit linear wear of the bearing which is equal to $h^* = 0.1 \text{ mm}$. We know the linear size of the elementary tribosystem— $D_{TS} = 2.85 \text{ mkm} = 2.85 \cdot 10^{-6} m$ [19]. For each revolution of the shaft one elementary tribosystem (equilibrium, run-in contact) loses one mechanical quantum. The number of revolutions required for the wear of one elementary tribosystem is equal to the number of mechanical quanta in this tribosystem, that is, it is $n_{MQ} = 0.63 \cdot 10^8$ revolutions.

Now we can determine the wear time of one elementary tribosystem:

$$t_{TS} = \frac{n_{MQ}}{n} = \frac{0.63 \cdot 10^8}{1500} = 42,000 \text{ min} = \frac{42,000}{60} = 700 \text{ hour} = \frac{700}{24} = 29,166 \text{ day}$$
$$= \frac{29,166}{365} = 0.0799 \text{ year.}$$

(50)

Now let's define the number of layers of elementary tribosystems into linear wear—0.1 mm:

$$a_{h^*} = \frac{h^*}{D_{TS}} = \frac{1 \cdot 10^{-4}}{2.85 \cdot 10^{-6}} = 0.35 \cdot 10^2 = 35.$$
(51)

Now, let's define the time of wear of shaft-bearing system with the ultimate linear given wear— $h^* = 0.1$ mm, namely:

$$t_{motor} = t_{TS} \cdot a_{h^*} = 0.0799 \cdot 35 = 2,7968 \text{ year.}$$
(52)

Finally, we have 2, 7968 years of continuous work at ultimate load. For this result we have the wear rate—i = 4 nm/h. For example, this fits well with the data for the engine wear rate—i = 5 nm/h specified by Prof. F. Franek [20].

If we work 8 hours per day, then we will get the following result:

2,
$$7968 \cdot 3 = 8.39$$
 year. (53)

This is a real result for modern cars. If we work less than 8 hours a day, then the duration will increase significantly.

5.3 The principle of critical wheel rolling speed

The limit of this speed is determined by the principle of filling the entire nominal friction area of the sliding system with elementary tribosystems damping the process. Above this speed of movement of the vehicle there will be a complete unloading of the tribosystem, the separation of the wheel from the rail surface, since the principle of minimum resistance to movement (the principle of one elementary tribosystem or the principle of irreversibility) will be violated. In this case, all mechanical quanta in the elementary tribosystem will repel the wheel. There will be no quantum activating the process of maintaining the system in an excited state.

The calculation will be made in the following order [21]. The elementary nominal size of the contact area is known. By definition [4], $n_*^{TS} = 0.63 \cdot 10^8$ elementary tribosystems can be placed and operate on the elementary nominal contact area. Each elementary tribosystem (for the model of spherical roughness) has a size $D_{1TS} = 2.85 \cdot 10^{-6} m$ [19] and is capable of providing a rolling path of the wheel in the elementary act of rolling on the length of this tribosystem.

Thus, if all elementary tribosystems work in a unit of time on the entire nominal contact area, then the path traversed by the wheel in a unit of time is equal to

$$L_{\Sigma TS} = D_{1TS} \cdot n_{TS}^* = 2.85 \cdot 10^{-6} \cdot 0.63 \cdot 10^8 = 179.55 \, m. \tag{54}$$

Consequently, the critical speed of wheel rolling is equal

$$\mathbf{v}_* = L_{\Sigma TS} \cdot 3600 = 646, 38 \ km/h. \tag{55}$$

This result is close to modern speed of 574.8 km/h (TGV, France).

5.4 Self-organized nanoquantum solid lubricant

Information above allows us to consider new self-organized surface layer as follows: (1) the layer that separates the two original surfaces (alloys) of friction



Figure 11. Notional scheme of hydrodynamic lubrication.

from each other; (2) layer, which has a low coefficient of internal friction; (3) layer, which has a high capacity for work, that is, very small wear; and (4) layer, which may be seen as a solid lubricant.

Now you need to determine a value for the coefficient of friction of this selforganized solid lubricant and compare it with the coefficient of friction, for example, the most effective, or hydrodynamic lubrication.

It is known that the hydrodynamic lubrication when the stationary condition (**Figure 11**) has coefficients of friction μ down to 0.005÷0.001 values.

For nanoquantum self-organized solid lubricant friction coefficient will be calculated in the following order:

1. It is known [4, 15] that between the nanoquanta coefficient of friction is equal to $\mu_{MO} = 1.587 \cdot 10^{-8}$.



Figure 12.

Conditional scheme for equilibrium elementary tribosystem, structured mechanical quanta. At length of this tribosystem there are 397 mechanical quantums.

- 2. It is known [19] that the size of the critical volume of frictional contact (elementary tribosystem) is equal to $D_{TS} = 2.85 \cdot 10^{-6} m$.
- 3. Let's picture an elementary tribosystem in the plane as a circle with a diameter of $D_{TS} = 2.85 \ mkm$ (Figure 12).
- 4. Next, let's define the number of mechanical (nano) quanta n'_{MQ} on a length D_{TS} of elementary tribosystem (**Figure 12**):



Figure 13.

Notional scheme of friction on the wavelength, structured elementary tribosystems. At the surface friction wavelength is 351 elementary tribosystems.





5. Let's define the coefficient of friction for a single equilibrium critical volume of friction (elementary tribosystem), the length of which is 397 mechanical quantums (**Figure 12**).

$$\mu_{TS} = \mu_{MQ} \cdot n'_{MO} = 1.587 \cdot 10^{-8} \cdot 397 = 0.63 \cdot 10^{-5}.$$
 (57)

6. Let's take the average friction surface wavelength equal to $L_W \cong 1 \cdot 10^{-3} m$.

Now define a number of elementary tribosystems on this wave length (Figure 13)

$$n_{TS} = \frac{L_W}{D_{TS}} = \frac{1 \cdot 10^{-3}}{2.85 \cdot 10^{-6}} = 351.$$
(58)

7. Now define friction coefficient at a wavelength of friction surface

$$\mu_W = \mu_{TS} \cdot n_{TS} = 0.63 \cdot 10^{-5} \cdot 351 = 0.0022 \tag{59}$$

As a result, we have a full conformity (**Figure 14**) of friction coefficient values for hydrodynamic lubrication—0.005÷0.001 and solid lubricant—0.0022.

Thus, it is fair to talk about nanoquantum self-organized solid lubrication.

6. Conclusions

- 1. Structural-energy analysis of the friction process allows us to consider the friction process as an evolutionary process.
- 2. From the equations of the energy balance of friction it follows that the evolution of the tribosystem (contact) has an adaptive-dissipative character.
- 3. The coefficient of friction has an energy interpretation that reveals its deep physical sense.
- 4. Experimental friction curves of $\mu = \mu(N, v)$ type may be examined as generalized friction experimental curves.
- 5. Structural-energy diagram of the evolution of rubbing surfaces (friction contact) interprets the general regularities of transformation and dissipation of energy during friction.
- 6. In the process of evolution of the friction contact, an elementary tribosystem is formed as a self-sufficient energy transformer under friction. This elementary tribosystem (critical friction volume) can be considered as an analogue of the material point of mechanics.
- 7. The most complete evolution of the tribosystem has a symmetrical form—the friction process begins and ends in the elastic region.
- 8. With the most complete evolution of the friction contact (elementary tribosystem), a unique nanostructure (tribosubsystem) is formed; the basis of this nanostructure is a mechanical (nano) quantum and the friction contact (material point of mechanics) consists of about 0.63 · 10⁸ such nano quanta.
- 9. We can consider the mechanical quantum as the smallest structural form of a material solid and as the structural standard of material solid.

- 10. The mechanical quantum is precisely an asymptotically stable attractor of the limit cycle type for a deformable solid body (at friction).
- 11. All parameters of compatibility (optimal) friction have to be in quanta levels —commensurable with the parameters of the one mechanical quantum.
- 12. Interaction between nanoquantums is nature the net elasticity. The value of the coefficient of friction between mechanical quanta has order $\mu_{MO} = 1.587 \cdot 10^{-8}$.
- 13. Exploitation of gear wheels and other heavy-loaded tribosystems (Hertzian contact) are subjected to model of nano-quantum damping, when one mechanical quantum is the standard of contact structure and wear.



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