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RESEARCH

Nano-Structural Standard of Friction and Wear

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A B S T R A C T

At the most full evolution of tribocontact the unique nanostructure (subtribosystems) is formed and the basis of which is one mechanical (nano) quantum. Mechanical quantum represents the least structural form of solid material body in conditions of friction. It is dynamic oscillator of dissipative friction structure and can be examined as the elementary nanostructure of metal's solid. At friction in state of most complete evolution of elementary tribocontact all mechanical quantums with the exception of one elasticity and reversibly transform energy of outer impact (mechanic movement). In these terms only one mechanical quantums is the lost – standard of wear. Some practical examples with using of mechanical quantum idea as standard of wear are considered.

1. INTRODUCTION

When exploitation of friction pair a contact is deformed and its states and properties are changed too. From the structural-energy interpretation of friction process point of view a contact of friction has evolution regularities. It is determined by competition of two opposite interrelated and simultaneous trends: growth of latent energy density of various defects and damages which are generated and accumulated in the material due to work done by the external forces and reduction (release) of the density as a result of relaxation processes in deformed body element. The first trend is concerned with strain hardening and damage of material, the second - with dynamic recovery and dissipation of the strain energy which govern the thermal effect of plastic deformation. During evolution contact process the size of wear particles are changed. Minimum wear has the contact at term of most full evolution. It is maximum adaptation. Minimum wear particle size should be considered as the standard of wear.

2. TRIBOERGODYNAMICS METHOD

This paper in its basis is a logical completion of axiomatic analysis of sliding friction (rolling)

within the framework of triboergodynamics, a scientific trend suggested by the author [1-3].

The general evolution regularities of states and properties of tribosystem in the frame of triboergodynamics are analysed. Triboergodynamics is based on our modern knowledge of friction: 1. friction is a phenomenon of resistance to relative motion between two bodies, originating at their surfaces contact area; 2. friction is the process of transformation and dissipation of energy of external movement into other kinds of energy; 3. friction is the process of elasto-plastic deformation, localized in thin surface layers of rubbing materials.

Methodology of triboergodynamics [1-3] is based on the analysis method to plastic deformation of ergodynamics of deformed solids [4]. Ergodynamics 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.

Within the framework of triboergodynamics the model of elastic-plastic deformation of contact volumes is examined as a generalized mechanism of transformation and dissipation energy and determines essence of resistance to surfaces displacement.

Friction is regarded as a global (energy) phenomenon of relative movement transformation. It strongly obeys equation of energy balance and from thermodynamic point of view it is a competition of two simultaneous, interconnected and opposite tendencies of accumulating latent (potential) energy ΔU_e of various kinds of defects and damages of contact volumes structures and releasing (dissipation) energy Q due to various relaxation processes.

According to the energy balance scheme (Fig. 1) for plastic deformation and fracture [2,4] presented below, equations for friction work W_f, frictional force F and friction coefficient μ (without lubrication) has view:

$$W_f = \Delta U_e + Q = \Delta U_{e_1} + \Delta U_{e_2} + \Delta U_{T_1} + \Delta U_{T_2} + \vec{Q}_1 + \vec{Q}_2 \quad (1)$$

$$\dot{W}_f = \dot{U}_e + \dot{Q} = \dot{U}_{e1} + \dot{U}_{e2} + \dot{U}_{T_1} + \dot{U}_{T_2} + \dot{\vec{Q}}_1 + \dot{\vec{Q}}_2 \quad (2)$$

$$F_l = \frac{\Delta U_e}{l} + \frac{Q}{l} = \frac{\Delta U_{e_1} + \Delta U_{e_2}}{l} + \frac{Q_1 + Q_2}{l} \quad (3)$$

$$F_v = \frac{\dot{U}_{e_1} + \dot{U}_{e_2}}{v} + \frac{\dot{Q}_1 + \dot{Q}_2}{v} = F_{mechanical} + F_{molecular} \quad (4)$$

$$\mu_l = \frac{\Delta U_{e_1} + \Delta U_{e_2}}{Nl} + \frac{Q_1 + Q_2}{Nl} = \mu_{adapt} + \mu_{dis} = \mu_{adapt} + \mu_{T(dis)} + \mu_{\dot{Q}(dis)} \quad (5)$$

$$\mu_v = \frac{\dot{U}_{e_1} + \dot{U}_{e_2}}{Nv} + \frac{\dot{Q}_1 + \dot{Q}_2}{Nv} = \mu_{deformation} + \mu_{adhesion} \quad (6)$$

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

Thus, viewed thermodynamically [1-3], 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 classified conventionally into two specific components with different kinetic behavior [4-6]. The first component is associated with microscopic mechanisms of adaptive type and relates to the change of latent (potential) energy ($\Delta u_{e1}, \Delta u_{e2}$) of various elementary defects and damages that are generated and accumulate in the deformable volumes of materials friction pair (Fig. 2). This energy is a unique and integral characteristic of the submicro- and microstructural

transformations that occur in plastically strained materials [4-6]. This energy is a measure of strain hardening and damageability of materials.

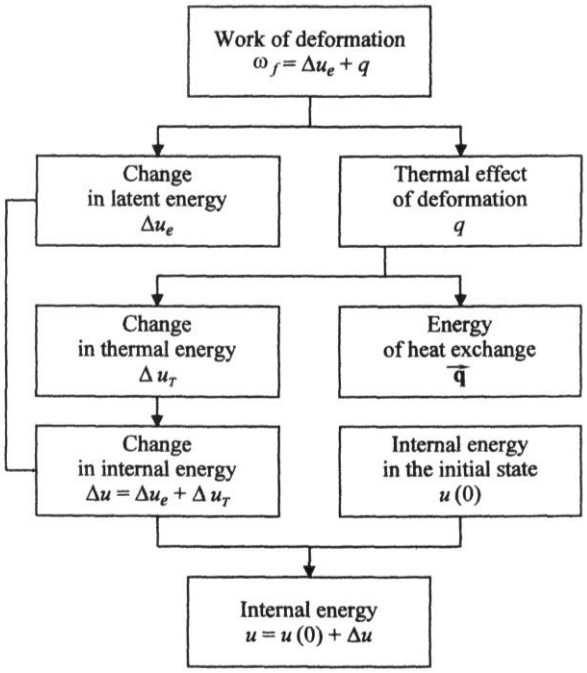

Fig. 1. Scheme of the energy balance for the plastic deformation of a solid body [1-4].

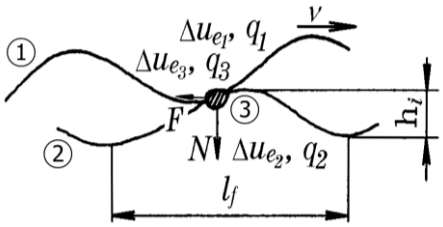

Fig. 2. Schematic view of elementary friction's contact [1].

The second component is associated with microscopic mechanisms of dissipative type and relates to dynamic recovery processes in which latent energy is released and heat effect of friction (q_1, q_2) take place. This energy originates in the motion and destruction of various elementary defects of opposite signs, the egress of these defects to the surface, the healing of reversible submicroscopic discontinuities, etc. The ratios of the components Δu_{e1} and Δu_{e2} 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.

Thus, the thermodynamic analysis of friction (plastic deformation and fracture) has led to generalized (two-term) relations (1)-(6) for the force F and coefficient of friction μ, which agrees with current concepts of the nature of friction.

Relationships (1)-(6) which generalize the mechanism of energy dissipation at friction allow classify the tribosystem states. According to ergodynamics of deformed solids (relationships $\Delta u = \Delta u_e + \Delta u_T$ and $q = \Delta u_T + \vec{q}$) and equations (1)-(6), all exhibitions of friction and wear may be reduced conventionally at least to two basically different states: the first state defines all types of damage and wear, the second — the so-called "wearless" condition. The state of damage and wear is characterized by the components of energy balance (1)-(6), 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, i.e. the process is irreversible. The "wearless" state is characterized by the components responsible for dynamic dissipation (reversibility) of strain energy into elastic and structural dissipated energy $\vec{q} = \vec{q}_1 + \vec{q}_2$ of friction contact.

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 Δu_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 quasi-brittle or quasi-ductile fracture of solids.
In the most general case, the energy balance at dry friction (1) should be written as:

$$W_f = \Delta U_{e1} + \Delta U_{e2} + \Delta U_{e3} + Q_1 + Q_2 + Q_3 \qquad (7)$$

In the special case, where the friction is localized into volume of the "third body" equation (7) develops into:

$$W_f = \Delta U_{e3} + \vec{Q}_3 \qquad (8)$$

According to thermodynamic theory of strength [4], the damageability parameter and the fracture criterion are defined in terms of the internal energy density u accumulated within the strained element of a solid body. A solid body is assumed to suffer fracture if the internal energy density has reached a critical value u^* in at least a single macrovolume that is responsible for fracture.

3. ENERGY INTERPRETATION OF LEONARDO DA VINCI (AMONTON'S) FRICTION COEFFICIENT

According to thermodynamic theory of strength [4], the structure parameter should be related to the portion of the accumulated plastic deformation that is responsible for strain hardening. This portion is uniquely and integrally defined by the density of the potential component of internal energy (that is, the latent energy Δu_e density) of various defects and damages that accumulate in a plastically strained material. With this in mind, if we neglect the heat effect Q of friction, one will infer from the thermodynamic analysis of friction of equations (1)-(6) that the Amonton (Leonardo da Vinci) friction coefficient is:

$$\mu = \frac{\Delta U_e}{\mu^* N l} = \frac{F}{N};\ F = \frac{\Delta U_e}{l};\ Q \cong 0,\ \mu^* = 1. \qquad (9)$$

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 $\mu^* N l$ (energy of external relative movement). 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.

Therefore, coefficient of friction is a true and generalized parameter of tribosystem state. From this conclusion we can say that the analysis of the evolution of the states of a tribosystem is primarily an analysis of the latent deformation energy accumulated within the contact friction volumes.

4. ENERGY REGULARITIES OF RUBBING SURFACES EVOLUTION

An analysis of modern experimental data using equations (1)-(9) has shown that the experimental friction curves of type $\mu = \mu(N, v)$ are the generalized friction curves that reflect the evolution (the change in the friction coefficient) of tribosystem.

We propose an energetic interpretation of the experimental friction curves $\mu = \mu(N, v)$ (Fig. 3).

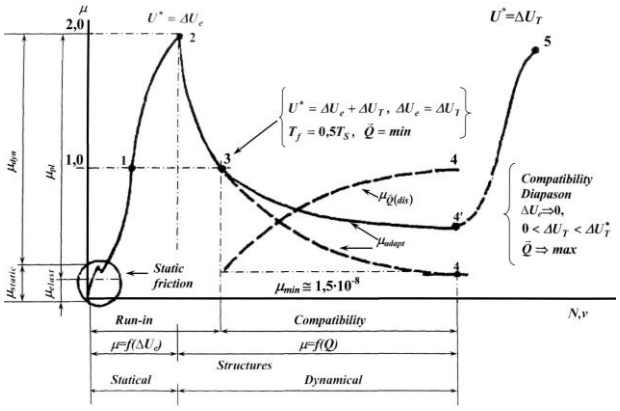

Fig. 3. Structural-energy diagram for evolution of rubbing surfaces [1-3]. μ_{stat}; μ_{dyn}; μ_{elast}; μ_{plast} – static, dynamic, elastic, plastic friction coefficients correspondingly; T_f; T_S – ignition (flash) temperature in contact friction volume in point 3 and melting temperature.

According to our concept [1-3], 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} $(\vec{q}^* = u_e^*)$.

Tribosystem evolution presented as a diagram (Fig. 3), has adaptive-dissipative character (1) and reflects competitive, (dialectical) nature of friction. Evolution curve has a set of principal points (1-5) of transitive states of tribosystem, which strongly obeys a balance principle of friction. The most characteristic areas between these points reflect general properties of its non-linear dynamics.

So, in Fig. 3 it is possible to see the following conventionally designated points and stages: 0-1 – a stage of static friction and deformational strengthening; 1 – a point of limit for deformational strengthening; 1-2 – a stage of pumping of excess energy; 2 – a point of gripping (adhesion) and transition of outer friction into internal (critical non-stability): 2-3 – a stage of forming dissipation structures (formation of heat fluctuation in friction volume); 3 – a point of minimum compatibility (maximum frictionness); 1-2-3 - a stage of selforganization; 3-4 – a stage of compatibility; 4 – a point of wearlessness (anormal-low friction); 5 – a point of thermal adhesion.

An ideal evolution of tribosystem is symmetrical. The process starts and finishes within areas of elastic behavior. A plastic maximum (a superactivated condition) exists between them as a condition of selforganisation and adaptation.

In the most general case evolution (adaptation) regularities of tribosystems may be presented as a 2-stage (Fig. 3). At the first stage (0-2) of adaptation the evolution of friction contact rushes to form some critical volume of friction V_f^* (point 2). It is elementary tribosystem that is the elementary and self-sufficient energy transformer. The first stage - latent energy density growth Δu_e to a limited magnitude Δu_e^* within critical friction volume V_f^*.

This friction volume V_f^* is constant at the second stage of evolution, but here it is evolutionary developed owing to structural transformation; by this one may realize wide spectrum of compatibility friction structures (Fig. 3).

The second stage (2-4) – structural transformation of critical friction volume (elementary tribosystem) V_f^* into adaptive V_{adapt} and dissipative V_{dis} volumes. The limit (point 4) of this stage is characterized by a full transformation of adaptive critical volume V_{adapt}^* into V_{dis}^* dissipative.

The volumes mentioned above characterize different regularities of transforming energy of outer mechanical movement at friction. Adaptive volume V_{adapt} is connected with non-reversible absorption of deformation energy. It is in this volume where latent deformation energy Δu_e accumulates and where the centres of destruction initially emerge (birth). Dissipative volume V_{dis} is capable of reversible transformation (dissipate) of outer movement energy. It doesn't accumulate latent deformation energy owing to reversible elastic-viscous-plastic deformation.

Suggested theoretical and calculation assessments [1-3,7-9] showed that dissipative friction volume performs reversible elastic energy transformation of outer mechanical movement with density $\vec{q}^*$ equal to critical density of latent energy u_e^*.

Culmination of tribosystem evolution is its final and limited condition of point 4 – a state of anomalously low friction and wearlessness (maximum efficient).

Calculation show [1-3] that at an ideal tribosystem evolution an adaptive (Amontons)

friction coefficient μ_{adapt} in a point 2 of a diagram falls abruptly down, reaching in a point 4 the value of elastic friction coefficient μ_{elast}. For point 4 of compatibility area 3-4 an equation of energy balance (1) showed be put in the following way:

$$\mu_{adapt} = \mu^* - \mu_{dis} = \\ = 1 - \mu_{dis} = \mu_{plast} = 0 = \mu_{elast};\ \mu^* = 1{,}0 \quad (10)$$

Thus, point 4 stands for an ideal evolution of contact friction volume a condition of ideal elastic-viscous-plastic deformation. Equation (10) shows as a matter of fact exactly it, i.e. Amontons friction coefficient μ_{adapt} being in its essence plastic friction coefficient μ_{plast} has a minimum value equal to zero. It follows then, that plastic friction became elastic with friction coefficient μ_{elast}. It means that plastic deformation of contact volume friction is implemented with the maximum dynamic dissipation ($\vec{Q} = \max$) of accumulated latent energy. That is why the value of accumulated energy in point 4 is equal to zero ($\Delta U_e = 0$). This fact proves an ideal condition at most full evolution of contact volume. From the physics point of view this condition may be explained by the full dissipation of accumulated energy ΔU_e^* in point 2 and by newly emerged structures of point 4 in the form of elastic energy of interaction between them (dynamic dissipation energy $\vec{Q}^*$). Here, $\mu_{dis} = 1{,}0$. The structural elements themselves are defectlessness - $\mu_{adapt} = 0$, and friction is elastic - $\mu = \mu_{elast}$.

It has been demonstrated [2,3,7-9] that value of minimum adaptive friction volume $V_{adapt}^{\min}$ corresponding to the zero meaning of plastic friction component μ_{adapt} is not equal to zero, but is equal to some minimum structural element of deformed solid body.

5. THE IDEA OF 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 notions about mechanical quantum have been obtained [2,7-9] considering equation of quasiideal solid body for point 4 of diagram of friction evolution:

$$\vec{Q}^* = \vec{S}_Q T = \mu_{dis}^* N l_f = V_f^* u_e^* = V_f^* \vec{q}_* \quad (11)$$

which is particular case of solving equation of energy friction balance (1) at $\mu_{adapt} = 0$ and $\mu_{dis} = 1 = \mu_{dis}^*$. Here $\vec{S}_Q$ – inertia entropy of compatible friction volume; T - characteristic temperature of contact friction volume; l_f - linear size of elementary contact.

Correspondingly, in conditions of maximum compatibility (point 4) when tribosystem implements full evolution cycle of adaptation with formation of most perfect dissipative structure, the behaviour of structure is subject to equation of quasiideal solid body condition. So, it is to be presumed that, interaction between elements of this structure, are minimized – a condition of ideal elasticity in dynamics. Equation (5) with taking into account Plank-Boltzmann formula $S = k \ln W$ and real number of atoms oscillators N_f in the volume of elementary tribosystem (contact) V_f^* is brought to the form explaining friction regularities from the point of view of system evolution:

$$\mu_{\text{diss}} = \frac{\vec{S}_Q T}{N l_f} = \frac{k T N_f \ln W}{N l_f} \quad (12)$$

$$\mu_{adapt} = 1 - \mu_{diss} = 1 - \frac{k T N_f \ln W}{N l_f} = \\ = 1 - \frac{\vec{S}_Q T}{N l_f} = \frac{S_U T}{N l_f} \quad (13)$$

Where k - Boltzmann constant; W - condition probability; S_U - configuration entropy of friction (contact) volume.

Tribosystem always tends to some optimal condition, characterized, i.e. to a most probable condition $W' = N_f \ln W$ for the given friction conditions.

Analysis and solution of these equations [2,7-9] allows to demonstrate the principle of constant

probability value (parameter of tribosystem condition (order)) W for the whole range of compatible friction precisely $\ln W = 3$ and $W = \mathrm{e}^3 = 20{,}08553696\ldots$

The value of thermodynamic probability W equal to $20{,}08553696\ldots$ was interpreted [2,3,7-9] as a minimum value of linear, atomic oscillators in one of three directions of minimum adaptive friction volume $V_{adapt}^{\min}$ corresponding to condition of practically absolute elastic friction – anomalously-low friction (safe deformation threshold). Then the number of atomic oscillators in this volume equals $V_Q = \left(\mathrm{e}^3\right)^3 = (20{,}08553695..)^3 = 8103{,}083969$ atom's oscillators.

It is the universal size (volume) of mechanical quantum [2,3,7-9].

On the other hand, adopting the meaning of Boltzmann entropy S, a universal friction constant $R_f = kN_f$ [2,3,7-9] is obtained, which characterizes in physical meaning «energetical size» of elementary tribosystem (TS), containing in ideal conditions the same number of atomic oscillators N_f (mechanical quanta N_Q):

$$R_f = k \cdot N_f = k \cdot W^3 \cdot N_Q = R_{MQ} \cdot N_Q, \quad \left(\frac{\mathrm{J}}{\mathrm{grade} \cdot TS}\right); \tag{14}$$

$$R_{MQ} = k \cdot W^3, \quad \left(\frac{\mathrm{J}}{\mathrm{grade} \cdot MQ}\right), \tag{15}$$

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

As it follows from calculations [2] the size of minimum adaptive friction volume $V_{adapt}^{\min}$ coincides in its value with the size of submicroscopic area in crevice mouth, which is equal for metals $(4\ldots9)\cdot10^{-6}$ mm, i.e. of critical volume size responsible to fracture. Thus the size of minimum adaptive friction volume $V_{adapt}^{\min} = V_{elast}$, can be presented as the size of some mechanical quantum.

This mechanical quantum constitutes a minimum number of atoms capable to provide such a configurational distribution (structure) which obtains the property of reversibly taking and dissipating (recovering) energy of outer mechanical movement. It also constitutes minimum structure form of solid material body in conditions of plastic deformation (friction) and it is formed at tribosystem transition (deformed volume) through an ultimately activated (critical) condition (see Fig. 3) due to development of selforganisational tribosystem adaptation processes. Mutual rotation-oscillation movement of these mechanical quanta in respect of each other within elementary tribosystem (contact) determines condition of most perfect dissipative friction structure. Properly speaking, such condition is described by equation of quasiideal solid body condition (9), a condition when interaction between structural elements (mechanical quanta) is minimized – a condition of ideal elasticity of quasiviscous flow. Calculation friction coefficient between quanta equals about 10^{-8} [2,3,7-9].

Table 1. Parameter W for Metals and Steels [3].

Metals and steels	$E \times 10^{-3}$, MPa	$\left(u_e^*\right)\Delta H_S \times 10^{-3}$, MJ/m³	$E / 3E_r$
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
Co	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
Mo	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

$\Delta H_S = 3E_r$, $E/3E_r = 20{,}77$.

A conclusion that mechanical quantum constitutes a minimum structural form at plastic deformation (friction) is supported by calculation. If values of elasticity modules E correspond to atomic (true) elastisities E_r then values equal to 60 are obtained, where $60 = 3W$ can be interpreted as a characteristic of volume elasticity of one mechanical quantum – minimum adaptive friction volume $V_{adapt}^{\min}$. Calculation assessment of parameter $W \cong 20 = E/3E_r$, done for various metals and steels gives an average value 20,77 (Table 1); $\Delta H_S = 3E_r$ - entalpy of melting.

A conclusion is made [2] that the number of atoms (mechanical quantum (MQ)) within volume of one elementary tribosystem (TS) in conditions of ideal tribosystem evolution is a constant value. Thus, it is possible to speak about the quantity of substance equal by mass to one elementary tribosystems and to one mechanic quantum.

6. SYNERGISM OF TRIBOSYSTEM AND STATE OF OPTIMUM

Mechanical quantum is dynamic oscillator of dissipative friction structure. An ideal quasielastic contact condition at its full evolution constitutes effect of most fully dissipated energy of outer mechanical movement throughout newly formed (by mechanism of selforganization) structural elements – mechanical quantums (dynamic oscillators) which most fully realize their rotationary – oscillatory behavior in relation to each other within elementary tribosystem volume. Their resistance to relative interaction here is minimally elastic and corresponds to elasticity of ideal atomic (thermodynamically balanced) interactions at the level of electron orbits.

Universal constants of mechanical quantum and elementary tribosystem (material point) determine quantum model of surface damping:

$$\mu_{dis} = \frac{3R_{MQ}T_{n_i}}{Nl_f} = \frac{U_{1Q}n_i}{U_{1Q}n_*} = \frac{n_i}{n_*} = 1 - \mu_{adapt},$$

$$\mu_{adapt} = 1 - \frac{n_i}{n_*} = \frac{n_{dest}}{n_*} \qquad (16)$$

taking into account destruction quantums n_{dest} (non-reversible process component) and damping quanta n_i (reversible, elastic component – fatique number), and also probability evolution tribosystem model to a most ordered condition:

$$\mu_{adapt} = 1 - \mu_{dis} = 1 - \frac{R_f T \ln W_i}{Nl_f} = 1 - \frac{\ln W_i}{\ln W_*} \qquad (17)$$

where $3R_{MQ}T = U_{1Q}$ - energy of one mechanical quantum; W_i and W_* - current and ultimate probabilities of tribosystems compatibility conditions.

According to a model of quantum surface damping at friction in state of most complete evolution (adaptation) of elementary tribosystem all mechanical quanta with the exeption of one elasticity and reversibly transform energy of outer impact (mechanic movement). One mechanical quantum of radiation ($\cong 8103$ atoms) – is a minimum loss (essence of wearlessness or other wear primary standard).

Linear size of quantum is equal to diameter of spherical ideal crystal with atomic roughness:

$$D_{MQ} = 2 \cdot W \cdot \bar{d}_a \cdot (3/4 \cdot \pi)^{1/3} = 7{,}177 nm. \qquad (18)$$

Here $\bar{d}_a$ - mean atomic diameter for metals; $W = e^3$ - parameter of state for mechanical quantum [2,3,7-9].

Mechanical quantum (Fig. 4) can be examined as the elementary nanostructure of metal's solid body.

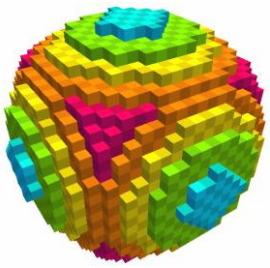

Fig. 4. Model of elementary nanostructure of friction (8103 atomic cubical cells) [2,3,7-9].

Calculations have shown [2,3,7-9] the number N_{MQ} 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.

In these terms (point 4) only one mechanical quantum [2,3,7-9] is the lost – standard wear. The tribosystem (friction contact) has the ideal damping properties – «wearlessness».

Consequently, the smaller the friction coefficient μ_{adapt} (the larger the coefficient μ_{dis}), the higher the fatigue endurance (durability) of a tribosystem, since more mechanical «quanta» are involved in damping (elastic recovery) of the energy of external mechanical motion and, consequently, fewer mechanical «quanta» take part in fracture (accumulation of the latent energy of defects and limiting damages). In the limit, a tribosystem features a «wearlessness» effect (anomalously low friction), which corresponds to a state of virtually complete thermodynamic reversibility of friction (deformation). Here, all the mechanical «quanta», except for one, reversibly and elastically transform (damp out) the energy of external mechanical motion. By analogy with classical quantum theory, one may say that in this case a tribosystem persists in the ground state (one may imagine all mechanical «quanta» pointed against the field); the tribosystem is incapable of transferring energy to any other system because the tribosystem accumulates no energy in this state. The tribosystem exists under conditions of virtually ideal equilibrium with the environment.

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

7. ENERGY POTENTIAL OF MECHANICAL (NANO) QUANTUM

Equation (11) demonstrates condition of total dissipation of accumulated friction volume V_f^* in point 2 (see diagram of Fig.3) defects energy with density u_e^* into dissipated energy along the newly formed structural elements (mechanic quanta) with density $\vec{q}^* = u_e^*$ of point 4. Thus, the amount of accumulated energy $U_e^* = V_f^* \cdot u_e^*$ in point 2 is equal to dissipated energy $\vec{Q}^* = V_f^* \cdot \vec{q}^*$ of point 4.

Since dissipated energy $\vec{Q}^*$ is distributed in the form of elastic energy among 63 million. mechanic quanta (dynamic oscillators), then it is possible to determine the amount of energy U_{1Q} accounting for one mechanic quantum, exactly:

$$U_{1Q} = \frac{U_e^*}{N_{MQ}} = \frac{\vec{Q}^*}{N_{MQ}} = \frac{U_e^*}{63 \cdot 10^6} = \frac{\vec{Q}^*}{63 \cdot 10^6} \quad (19)$$

Here we know the amount of critical friction volume V_f^* [9] equal to $12{,}194 \cdot 10^{-18}\ \mathrm{m}^3$ and magnitude of critical density of accumulated latent energy u_e^* [4] of for example steel $10{,}5\ \mathrm{J/mm}^3$.

We determine the amount of energy U_e^*, accumulated by critical friction volume V_f^*:

$$\vec{Q}^* = U_e^* = u_e^* \cdot V_f^* = \frac{10{,}5 \cdot 12{,}194 \cdot 10^{-18}}{1 \cdot 10^{-9}} = 128{,}039 \cdot 10^{-9}\ \mathrm{J/mm}^3 \quad (20)$$

Now it is possible to determine the amount of dissipation energy U_{1Q} accounting for one mechanic quantum:

$$U_{1Q} = \frac{U_e^*}{n^*} = \frac{128{,}037 \cdot 10^{-9}}{63 \cdot 10^6} = 2{,}032 \cdot 10^{-15}\ \mathrm{J} \quad (21)$$

The obtained amount of energy accounting for one mechanic quantum is elastic energy of its interaction with other quanta in its rotation-oscillating process as a dynamic oscillator of dissipative friction structures, i.e. it is surface energy of one mechanic (nano) quantum.

Since mechanic quantum is an ideal (free of any defects) and hence equilibrium structural formation, then it is natural that its internal energy is equal to its surface energy.

From this a conclusion is obtained: dissipated energy U_{1Q} accounting for one mechanic quantum at final and ideal evolution state of tribocontact is equal to its internal energy U_{1E}. Since theoretical crystal has only zero atoms oscillations, hence it is energy of zero oscillations.

Hence we obtain the following conclusion: the volume of theoretical crystal (tribosubsystem)

with zero atoms oscillations possesses the same magnitude of internal energy density as an ultimately deformed critical friction volume (distorted by ultimate density defects) with accumulated latent (potential) energy:

$$U_e^* = \Delta H_S \tag{22}$$

This fact serves as an additional argument for proving justice of strength theory [4]. Accumulated critical density of internal defects energy (structure distortions both static and dynamic) is a universal constant of material state, as this is at the same time the internal energy of an ideal crystal which is undoubtedly a constant.

The atom energy of its zero equilibrium oscillations is half kinetic and half potential energy. Thus it is possible to state that while formation of crystal structure defect re-distribution (transformation) of internal crystal energy to defects region takes place.

This fact absolutely strictly supports the basic logics of energy interpreting of strength concept of Professor Vasiliy V. Fedorov, according to which the work of external forces is expended for splitting atoms bonds of crystal grid, i.e. for forming defects.

Here it is quite appropriate to recall the following conclusion from monograph [5]: "So, there exists a principal difference between two fundamental notions: activated energy of elementary act of splitting atoms bonds and energy of splitting bond (vacancy formation). By energy of activation splitting of atom bonds we should understand work which is necessary to expend reversibly and isothermally, so as to put atom into activated (non-stable) state. As it has been pointed out this energy is equal $U = D_0/4$. If energy conveyed to atom bond is less than U, then split of the bond does not occur. If energy is equal or slightly more than U, then bond comes into unstable state capable of rupture. Ultimate bond splitting is this case is affected by way of "overpumping" of elastic energy from neighbouring, surrounding bonds. The magnitude of this energy varies within limits $0{,}25D_0 > \Delta W \geq D_0$ and depends on material structure and the type of crystal grid". Here ΔW - is non-reversible work expended for rupture atomic bond, D_0 - energy of dissociation bonds.

Here we determine the amount of energy U_{atom}, accounting for one atom of mechanic quantum. A mechanic quantum possesses 8103,... atoms. So:

$$U_{atom} = \frac{U_{1Q}}{8103} = \frac{2{,}032 \cdot 10^{-15}}{8103} = \\ = 2{,}468 \cdot 10^{-19}\ \text{J} = 1{,}54\ \text{eV} \tag{23}$$

The monograph by A.N. Orlov and J.V. Trushin [10] gives out experimental data [11,12] for energy of vacancy formation. For $\alpha - Fe$ it is $1{,}4\ \text{eV}$ and $1{,}5\ \text{eV}$, for $\gamma - Fe$, correspondingly $1{,}7\ \text{eV}$ and $1{,}5\ \text{eV}$; for $\delta - Fe$ it is $1{,}5\ \text{eV}$.

The mean value of vacancy formation energy here is equal to $1{,}52\ \text{eV}$.

As we see the discrepancy with the magnitude calculated above $U_{atom} = 1{,}54\ \text{eV}$, which is in sense energy of rupture bond (vacancy) is:

$$\frac{1{,}54 - 1{,}52}{1{,}52} \cdot 100\% = 1{,}3\%$$

This is a rather convincing result.

Looking at symmetry principle of ideal evolution of tribocontact (elementary tribosystem) we actually see that the process starts and finishes in region of pure elasticity.

At the beginning of tribosystem evolution we add a little reversible component of pure elasticity $\mu = \mu_{elast}$ to the process of plastic deformation from statics (initial state), and at the end of ideal (more complete) contact evolution ($\mu_{dis} = 1{,}0$) we return to the state of pure elasticity of the whole contact in dynamics with the loss (return) of the smallest particle of material solid body (system being deformed) – one mechanic (nano) quantum.

Thus, we can add or take some small amount of substance (one particle) energy in equilibrium and reversibly without performing work. This is really so, since it deals with pure elasticity. This particle's energy is called as chemical potential.

In other words, analysis of elementary tribosystem evolution (friction contact) demonstrates agreement of energy interpretation of friction process given in the

article to a well known J. Gibbs equation obtained for equilibrium processes.

8. AS TO THERMODYNAMICS OF TRIBOSYSTEM IDEAL STATE

In conditions of most full (ideal) equilibrium in point 4 (Fig. 3) the system has a loss – one mechanic quantum (one particle of a system). How are we to understand that? In other words, the condition of pure (structurally dissipated) elasticity at plastic deformation? Reversability (elasticity) and non-reversability (plastic deformation) together?

This is possible only in one easy – when one of the two may be neglected due to its insignificance. It may be minimum non-reversability i.e. the loss (one mechanic quantum) in conditions of pure (dissipative) elasticity. Or – this is a minimum reversibility, i.e. elasticity (initial at static contact) in conditions of plastic deformation. The first is the final state of contact evolution. The second is the initial state of its evolution.

Since these are two negligible then they are equal to each other. So, the minimum loss of one mechanic quantum is equivalent to initial elasticity i.e. reversibility. So adding to a system and also subtraction of one nano quantum is an effect equivalent to pure elasticity (reversability).

Accordingly, the work of such absolutely elastic effect is equal to zero. Now let us compare this conclusion with the formulation of chemical potential constitutes energy of adding one particle to a system without doing work.

Let us discuss up to which point the state of maximum dissipativeness of tribosystem (equilibrium far from the condition of equilibrium) of point 4 (Fig.3) corresponds to equation of J.W. Gibbs for equilibrium processes. Let us take one particle (ideal crystal) of a system with internal energy $U_{1E} = U_{1Q}$ of nanoquantum (see above) and multiply by the number of such particles N_{MQ} in the volume of elementary tribosystem (equilibrium friction contact). We shall get internal energy E of system (volume V_f^*) in its initial (before deformation) state:

$$E = U_{1E} \cdot N_{MQ} \tag{24}$$

Now let us perform work $\mu^* Nl$ on a system which will bring about change in the internal energy of system by magnitude ΔU_e^* (region 0-2 at Fig. 3). Then let us free accumulated energy ΔU_e^* in the form of energy of heating effect (in this case of dynamic dissipation) $\vec{Q} = TS$ (region 2-4 at Fig. 3), which reversibly will get back the system to the initial (elastic) state (but in a new structural form). Taking above mentioned into account we shall write (24) in the view:

$$E + \mu^* Nl - TS = U_{1E} \cdot N_{MQ} \tag{25}$$

or

$$E + \Delta U_e^* - \vec{Q} = U_{1E} \cdot N_{MQ} \tag{26}$$

In the result we will get a correlation:

$$U_{1E} = \frac{E + \Delta U_e^* - \vec{Q}}{N_{MQ}} = \frac{E + \mu^* Nl - TS}{N_{MQ}} = \\ = \frac{E}{N_{MG}} = \frac{G}{N_{MQ}} = \mu_{chem} \tag{27}$$

Which is known as a correlation for a chemical potential μ_{chem}.

Properly speaking, we get here that energy of one mechanic quantum is chemical potential. Internal energy of ideal (initial) system E (its heredity) is equal to critical accumulated, internal (free) energy ΔU_e^*, full melting heat ΔH_S and, accordingly, J. W. Gibbs potential G [6, 13-15]...etc.:

$$E = \Delta U_e^* = \Delta H_S = G \tag{28}$$

On the other hand if infinitly small amount of matter (mass) dm multiply by unit of energy referring to this mass $\frac{dU}{dm}$, then we will get infinitely small increment of system internal energy dU which is possible to add (take) at adding an infinitely small amount of matter:

$$\frac{dU}{dm} dm = dU \tag{29}$$

Now if we perform an infinitely small work of external forces PdV on the system and reversibly get it back in the form of infinitely

small heating effect TdS, then we can state the following:

$$\frac{dU}{dm}dm + Pdv - Tds = dU$$

Let us designate relation $\frac{dU}{dm}$ by parameter μ_{chem} and write the relation (30) in the form:

$$\mu_{chem}dm + PdV - Tds = dU \qquad (30)$$

In the result we will get J.W.Gibbs equation in its differential view for a case of equilibrium reversible process with a adding so small amount of matter dm, that S and V are kept constant $(dS = dV = 0)$. Here amount $\mu_{chem} = \left(\frac{dU}{dm}\right)_{S,V} = U_{1E}$ is known as a chemical potential.

The performed analysis of thermodynamics of ideal state of tribosystem reliably confirms the conclusion made in the paper, that the mechanic (nano) quantum is a molecule of metallic solids.

9. NANOQUANTUM MODELS OF TRIBOSYSTEM MAXIMUM CAPACITY FOR WORK

9.1 Gear wear calculation principle

The all parameters of compatibility (optimal) friction have to be in quanta levels - commensurable with the parameters of the one mechanical quantum – standard of wear.

So, all heavy-loaded tribosystems it is necessary to examine with position of tribosystem ideal evolution. This ideal state of tribocontact is true indicator of tribosystem state for practical examples of tribology. It is the standard of maximum tribosystems efficiency - anomalously low friction and wearlessness.

The state of friction contact under its most full evolution is the characteristic with exploitation of hard loaded Hertzian contact, for example, on the surfaces of gear wheels teeth and systems of wheel-rail and other. We can examine the active surface of gear wheel, which consist of equilibrium spherical form asperities after run-in. During one revolution of gear wheel each asperity of gear wheel teeth is loaded one time too. Under it the loss of one friction contact is equal to one mechanical (nano) quantum. Therefore, the whole contact volume is fatigue failured during about 63 millions cycles. The linear wear h_* of gear wheel is equal to diameter size $D_{TS} = 2{,}85 \cdot 10^{-6}$ m [16] of an equilibrium friction volume V_f^* (Fig. 5). It is the physical criterion of wear. One may understood that the constructive (limiting) criterion of gear teeth is equal to the limit bend strength of tooth. For example, it is about 0,3 modulus of gear wheel tooth.

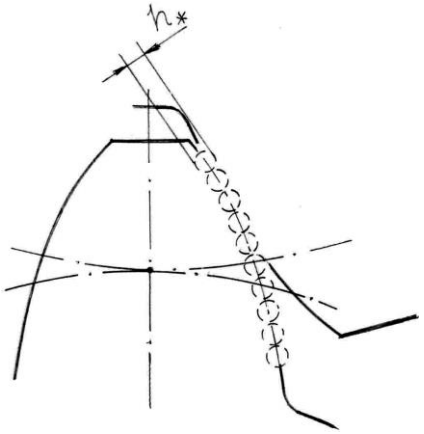

Fig. 5. Model of an active surface of gear wheel with equilibrium spherical form asperities.

Thus, an elementary nano-structure of deformed solids may examine as the standard of wear and to apply with optimization the life time of real hard pressed Hertzian contact systems.

9.2 Estimation of bearing capacity for work of internal combustion engines

Take the engine with a frequency of $n = 1500\text{min}^{-1}$ shaft rotation. Take the limit wear (linear) of bearing is equal to $h^* = 0{,}1\text{mm}$. We know the line size [16] elementary tribosystem: $D_{TS} = 2{,}85\text{mkm} = 2{,}85 \cdot 10^{-6}$ m. For every revolution shaft one elementary tribosystem (equilibrium, run-in contact) loses one mechanical quantum. The number of turns required to wear one elementary tribosystem equals the number of mechanical quantum in this tribosystem. So, there are $n_{MQ} = 0{,}63 \cdot 10^8$ revolutions.

Now you can define the time of wear for one elementary tribosystem:

$$t_{TS} = \frac{n_{MQ}}{n} = \frac{0{,}63 \cdot 10^8}{1500} = 42000\text{min} = \frac{42000}{60} = 700\text{hour} = \frac{700}{24} = 29{,}166\text{day} = \frac{29{,}166}{365} = 0{,}0799\text{year}$$

Now let's define the number of layers of elementary tribosystems into linear wear - $0{,}1\,\text{mm}$:

$$a_{h^*} = \frac{h^*}{D_{TS}} = \frac{1 \cdot 10^{-4}}{2{,}85 \cdot 10^{-6}} = 0{,}35 \cdot 10^2 = 35$$

Now, let's define the time of wear of shaft-bearing system with the ultimate linear given wear - $h^* = 0{,}1\,\text{mm}$, namely:

$$t_{motor} = t_{TS} \cdot a_{h^*} = 0{,}0799 \cdot 35 = 2{,}7968\text{year}$$

Total we have 2,7968 years of continuous operation on limit load.

If you work 8 hour per day, then we get the following result:

$$2{,}7968 \cdot 3 = 8{,}39\text{year}$$

This is a very real result for modern cars. And if the ride is not 8 hours per day and less durability increases considerably-really to decades.

For this result we have the wear rate - $i = 4$ nm/h. It is good correspondence with the data for wear rate - $i = 5$ nm/h by F. Franek [17].

9.3 The principle of critical velocity of rolling wheels

This speed limit is determined by the principle of filling the entire nominal friction sliding system area with elementary tribosystems, damping process. Above this speed happens full unloading tribosystem, detachment of wheels from the surface of the rail as distorts the principle of minimum resistance to movement (the principle of one elementary tribosystem or irreversibility). In this case, all mechanical quanta of elementary tribosystem will repel the wheel. There will be no quantum which activates a process to maintain the system in an excited state.

The calculation will be performed in the following order. Denote elementary nominal contact area. By definition [18], on elementary, nominal area of tribosystem can accommodate and work of $n_* = 0{,}63 \cdot 10^8$ elementary tribosystems. Each elementary tribosystem (for model of spherical roughness) has a size of $D_{1TS} = 2{,}85 \cdot 10^{-6}$ m and is able to implement rolling wheel path in the elementary act of rolling at length of this tribosystem.

Thus, if per unit of time all elementary tribosystems work on elementary nominal area of friction time, then the path passable wheel per unit of time, equal to:

$$L_{\Sigma TS} = D_{1TS} \cdot n^*_{TS} = 2{,}85 \cdot 10^{-6} \cdot 0{,}63 \cdot 10^8 = 179{,}55\text{m}$$

Consequently, the critical speed of wheel rolling is equal:

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

This result is close to modern speed of $574{,}8$ km/h (TGV, France).

10. CONCLUSIONS

Structural-energy analysis of the friction process allows us to examine the friction process as the evolution process;

From the energy balance equations of friction follows that the evolution of tribosystem (contact) has an adaptive-dissipative character.

Experimental friction curves of $\mu = \mu(N, v)$ type may be examined as generalized friction experimental curves. We may transform these curves to the view of structural energy diagram of rubbing surfaces evolution.

Most full evolution of tribosystem has symmetrical view - the friction process is started and finished within elastic area.

At the most full evolution of friction contact (elementary tribosystem) the unique nanostructure is formed; the basis of this structure is the mechanical (nano) quantum (ideal spherical crystal with atomic roughness) and the contact (material point of mechanics) consists of about $0{,}63 \cdot 10^8$ such quanta.

The size of elementary nanostructure (mechanic (nano) quantum) of solid body deformed at friction has been determined. It equals 8103,083969… atomic oscillators.

We can examine mechanic (nano) quantum as the least structural form of solid material body, structural standard of friction and the standard of wear.

Interaction between nanoquanta has nature the net elasticity. The value of the coefficient of friction between mechanical quanta has the order - $\mu_{MQ} = 1{,}587 \cdot 10^{-8}$.

We can examine mechanic (nano) quantum (subtribosystem) as the essence of J.W. Gibbs cell and it is interpreted as a molecule of metal solids which has own chemical potential.

Mechanic quantum of dissipative friction structures being the smallest particle of materially solid body may be viewed as a universal characteristic of solid material formation. This fact justly characterizes friction phenomenon as the simplest and universal nature phenomenon.

Exploitation of gear wheels and other heavy-loaded tribosystems (Hertzian contact) are subjected to model of nanoquantum damping, when one mechanical quantum of contact is the standard of wear.

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