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STRUCTURAL-ENERGY CONSTANTS OF THE EVOLUTION OF THE FRICTION CONTACT

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Abstract: *The structural-energy interpretation of the diagram of the evolution of the friction contact is shown. The diagram of the evolution of the friction contact reveals two principal stages of the adaptation of the friction contact. These two stages characterize the occurrence of two fundamental states of friction – maximum and minimum. The first stage of adaptation is due to the formation of the smallest deformable volume of friction, which has accumulated the maximum potential energy density of elementary defects and damage to the crystal structure. The second stage of adaptation is due to the formation of a unique nanostructural arrangement in this volume of friction, which is based on a mechanical quantum. The energy parameters of these two limiting states of friction contact are estimated. The universal energy constants of the limiting (adapted) states of the rubbing surfaces – friction contacts - are indicated.*

Keywords: *Friction, contact, structure, energy, evolution, adaptation, mechanical quantum, constant*

1. INTRODUCTION

Friction is a global transformational phenomenon of nature. The friction contact evolves during its operation. In the most general case, as a result of evolution, the contact organizes itself and adapts to its most advantageous structural and energetic state, ensuring maximum (or optimal) performance (endurance). The energy constants, the potentials of tribomaterials (tribopairs), determine a set of operational parameters during friction. What are the fundamental quantitative energy states of the friction contact and how are they formed during adaptation in the process of its evolution? Earlier, in a number of papers [1-3], it was shown how the thermodynamic analysis of the friction process (joint elastic-plastic deformation of friction surfaces) within the framework of the equations of energy balance, kinetics of the deformation process, and dislocation theory (Ergodynamics of deformed solids [4-6]) allowed us to present a diagram of the structural and energy evolution of friction surfaces (Figure 1). This diagram shows that the contact of friction during evolution due to adaptation passes through a number of limiting energy, potential states. Initially, an elementary tribosystem is formed – a critical volume of friction. The friction contact, accumulating the internal potential energy of defects in the crystalline structure, decreases in size to the smallest volume with a critical energy density. Then, this critical volume of friction evolves structurally in the limit to a set of elementary tribosystems – mechanical (nano) quanta. In this case, one energy state characterizes the

maximum possible friction, while the other state characterizes the minimum possible friction. These two energy states (equilibria far from the equilibrium state) are the results and essence of the two stages of adaptation of the friction contact during its evolution.

2. STRUCTURAL - ENERGY INTERPRETATION OF THE FRICTION PROCESS

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 (Figure 1) for plastic deformation and fracture [4-6] presented below, equations for friction work W_f , frictional force F and friction coefficient μ (without lubrication) has view

$$W_f = \Delta U_e + Q =$$

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

$$\dot{W}_f = \dot{U}_e + \dot{Q} =$$

$$= \dot{U}_{e_1} + \dot{U}_{e_2} + \dot{U}_{T_1} + \dot{U}_{T_2} + \dot{\vec{Q}}_1 + \dot{\vec{Q}}_2, \quad (2)$$

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

$$F_v = \frac{\dot{U}_{e_1} + \dot{U}_{e_2}}{v} + \frac{\dot{Q}_1 + \dot{Q}_2}{v} =$$

$$= F_{mechanical} + F_{molecular}, \quad (4)$$

$$\mu_l = \frac{\Delta U_{e_1} + \Delta U_{e_2}}{Nl} + \frac{Q_1 + Q_2}{Nl} =$$

$$= \mu_{adapt} + \mu_{dis} = \mu_{adapt} + \mu_{T(dis)} + \mu_{\bar{Q}(dis)}, \quad (5)$$

$$\mu_v = \frac{\dot{U}_{e_1} + \dot{U}_{e_2}}{Nv} + \frac{\dot{Q}_1 + \dot{Q}_2}{Nv} =$$

$$= \mu_{deformation} + \mu_{adhesion}, \quad (6)$$

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 $\mu_{\bar{Q}(dis)}$ - 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^*)).

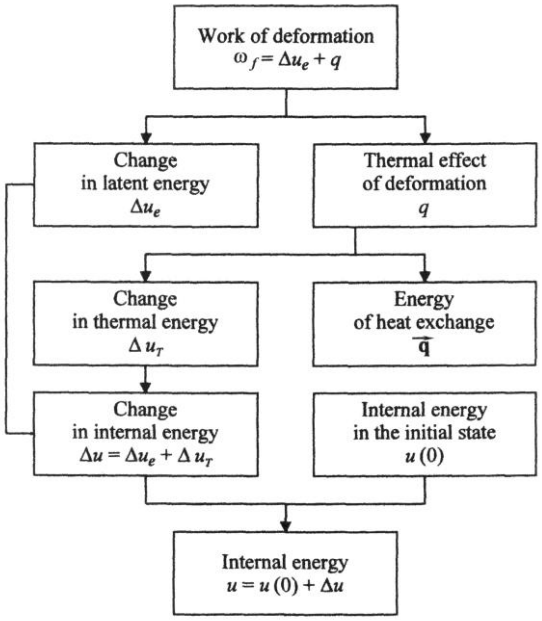

Figure 1. Scheme of the energy balance for the plastic deformation of a solid body [4-6]

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 (Figure 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. 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.

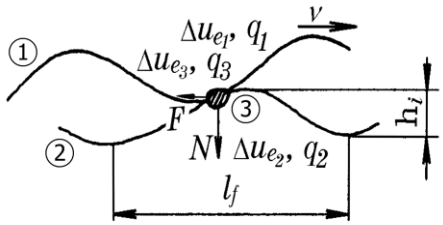

Figure 2. Schematic view of elementary friction's contact [1-3]

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 [6] (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 $\Delta u_e (\Delta u = \Delta u_e)$ 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 quasi-brittle or quasi-ductile fracture of solids.

In the most general case, the energy balance at dry friction (1) should be written as

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

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

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

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 [1-3], 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

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

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. STRUCTURAL - ENERGY DIAGRAM OF THE EVOLUTION OF FRICTION SURFACES

The equations (1)-(8) of the energy balance of friction [1-3] are considered as generalized equations of compatibility of rubbing surfaces, since they describe, in fact, the joint operation (deformation) of the surfaces of a friction pair.

These equations, transformed for the coefficient of friction (5)-(6), justify the general appearance of the structural-energy diagram of the evolution of friction surfaces (friction contacts (Figure 3)) [1-3].

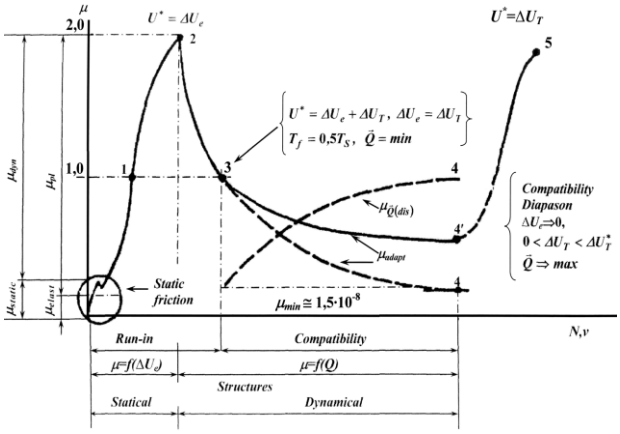

Figure 3. Structural-energy diagram for evolution of rubbing surfaces [1-3]. μ_{stat}; μ_{dyn}; μ_{elast}; μ_{plast} – static, dynamic, elastic, plastic friction coefficients correspondingly; T_f; T_S – ignition (flash) temperature in contact friction volume in point 3 and melting temperature.

In the diagram (Figure 3), the first limiting state is point 2, where we really have an equilibrium state far from equilibrium (zero compatibility of rubbing surfaces). Indeed, during evolution, the friction contact, passing through point 1 with extreme deformation (dislocation) hardening ΔU^*_{eD}, further evolves, accumulating the potential energy of nonequilibrium vacancies ΔU^*_{eV}. At point 2, the entire critical volume of friction V^*_f contains the maximum potential energy density of defects $\Delta u^*_e = \Delta u^*_{eD} + \Delta u^*_{eV}$,

where $\Delta u_{eD}^{*} = \Delta u_{eV}^{*}$. This is the point of maximum friction – adhesion in friction and elementary seizure – tearing out the volume V_f^* of an elementary tribosystem.

The size of this volume V_f^* is known - $12{,}194 \cdot 10^{-18} m^3$ [1-3], and the critical energy density Δu_e^* is also known, for example, for steel - $10{,}5\, J/mm^3$ [4].

The second limit state (the equilibrium is far from the state of equilibrium (zero)) it is located at point 4 of the ideal evolution of the critical volume V_f^* of friction (elementary tribosystem), where structurally this volume characterizes the state of an ideal solid body.
Here, in fact, under the condition of the ideal evolution of the friction contact, we have the condition of maximum dynamic dissipation of accumulated energy ($\mu_{dis}^{*} = 1{,}0$; here - $\mu_{adapt} = 0 = \mu_{elast}$) and the energy balance equation (5), (6) is written as the equation of a quasi-ideal solid [1-3]:

$$\vec{S}_Q T = \mu_{diss_{\vec{Q}}} Nl \qquad (10)$$

or

$$\vec{Q}^{*} = \vec{S}_Q T = \mu_{diss_{\vec{Q}}}^{*} Nl = V_f^{*} u_e^{*} = V_f^{*} \vec{q}_{*}. \qquad (11)$$

For these conditions, in the dissipative volume of an elementary tribosystem $V_{dis} = V_f^*$, the energy density $\vec{q}_*$ of dynamic (structural) scattering is equal to the critical density u_e^* of the accumulated potential energy of point 2 [1-3].

Accordingly, in conditions of maximum compatibility, when a tribosystem implements a complete evolutionary cycle of adaptation with the formation of the most perfect, dissipative structure, its behavior obeys the equation of state of a quasi-ideal solid, i.e. it should be assumed that interactions between the elements of this structure are minimized – the state of ideal elasticity [1-3].

Theoretical and computational analysis of energy transformation by an elementary tribosystem (deformable contact) [1-3] shows (Figure 3) that the ideal evolution of a tribosystem (a material point) begins and ends in elastic regions, between which there is a complete transformation cycle of evolution of the plastic (irreversible) friction component with point 2 of the highly excited state of the region 1-2-3 of self-organization.

With the ideal evolution of the tribosystem, the adaptive (Amontons) coefficient of friction μ_{adapt} drops sharply beyond point 2 of the diagram, reaching the value of the elastic coefficient of friction μ_{elast} (point 4), i.e.

$$\mu_{adapt}^{\min} = \mu^{*} - \mu_{lbss}^{\max} =$$

$$= 1 - \mu_{diss}^{\max} = \mu_{plast} = 0 = \mu_{elast}; \qquad (12)$$

It has been shown [1] that the value of the minimum adaptive volume $V_{adapt}^{\min}$ of friction corresponding to the zero value of the plastic component of friction $\mu_{adapt}^{\min}$ is not zero, but is equal to the size of some smallest structural formation corresponding to the state of ideal elasticity at the contact.

5. THE MECHANICAL QUANTUM OF DISSIPATIVE FRICTION STRUCTURES

As follows from the calculations [1], the size of the minimum adaptive friction volume $V_{adapt}^{\min}$ coincides in size with the size of the submicroscopic zone at the crack mouth, which is equal for metals $(4 \div 9) \cdot 10^{-6} mm$ [6], i.e. with the size of the critical volume responsible for fracture. Thus, the size of the minimum adaptive volume $V_{adapt}^{\min} = V_{elast}$ can be represented as the size of a certain mechanical quantum [1-3] (Figure 4).

This mechanical quantum represents the minimum number of atoms capable of providing such a configurational distribution (structure) that has the property of reversibly

absorbing and dissipating (returning) the energy of external mechanical motion (impact). It also represents the smallest structural formation under conditions of plastic deformation and is formed during the transition of a tribosystem (deformable volume) through an extremely activated (critical) state (Figure 3), due to the development of self-organizational processes of tribosystem adaptation. The size of the mechanical quantum was determined by [1-3] and is equal to 8103, ... atomic oscillators. The mechanical quantum as a structural element is a theoretical crystal of an atomically spherical shape.

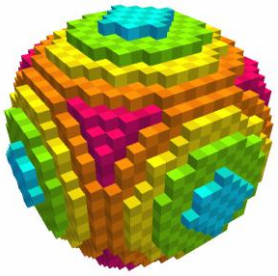

Figure 4. Model of elementary nanostructure of friction (8103 atomic cubical cells) [1-3]

6. ESTIMATION OF THE ENERGY POTENTIAL OF A MECHANICAL (NANO) QUANTUM

Equalities (10) and (11) for the ideal evolution of the friction contact show the condition for the complete dissipation of the accumulated energy of defects with a density u_e^* of friction volume V_f^* at point 2 (Figure 3), into structurally dispersed energy [1-3] by newly formed structural elements (mechanical quanta) at point 4 with a density $\vec{q}^* = u_e^*$. The size of the equilibrium contact (elementary tribosystem) in the 2-4 region is constant.

Thus, the amount of accumulated energy $U_e^* = V_f^* \cdot u_e^*$ at point 2 is equal to the dissipated energy $\vec{Q}^* = V_f^* \vec{q}^*$ of point 4.

Since this dissipated energy $\vec{Q}^*$ is distributed as elastic energy between about 63 million mechanical quanta N_{MQ} (dynamic oscillators) of one elementary tribosystem (critical friction volume) [1], it is possible to determine the amount of energy U_{MQ} per mechanical quantum, namely:

$$U_{MQ} = \frac{U_e^*}{N_{MQ}} = \frac{\vec{Q}^*}{N_{MQ}} = \frac{U_e^*}{63 \cdot 10^6} = \frac{\vec{Q}^*}{63 \cdot 10^6} . \quad (13)$$

Knowing the size of the critical friction volume V_f^* [1], equal to $12{,}194 \cdot 10^{-18} m^3$, and the value of the critical density u_e^* of accumulated latent energy [4], for example, for steel $10{,}5\, J/mm^3$, we determine the amount of energy accumulated by the critical friction volume V_f^*:

$$U_e^* = u_e^* \cdot V_f^* = \frac{10{,}5 \cdot 12{,}194 \cdot 10^{-18}}{1 \cdot 10^{-9}} = \\ = 128{,}039 \cdot 10^{-9}\, J . \quad (14)$$

It is now possible to determine the amount of scattering energy U_{MQ} per mechanical quantum:

$$U_{MQ} = \frac{U_e^*}{N_{MQ}} = \frac{\vec{Q}^*}{N_{MQ}} = \frac{128{,}037 \cdot 10^{-9}}{63 \cdot 10^6} = \\ = 2{,}032 \cdot 10^{-15}\, J . \quad (15)$$

The resulting amount of energy per mechanical quantum is the elastic energy of its interaction with other quanta in its rotational–oscillatory process as a dynamic oscillator of dissipative friction structures, i.e. it is the surface energy $U_{MQ_{sur}}$ of one mechanical (nano) quantum.

Since a mechanical quantum is an ideal (defect-free) and, consequently, an equilibrium, spherical structural formation, its internal energy $U_{MQ_{int}}$ is naturally equal to its surface energy $U_{MQ_{sur}}$.

Hence, we conclude that the structurally dissipated energy U_{MQ} per mechanical quantum in the final and ideal evolutionary state of a tribocontact is equal to its internal energy $U_{MQ_{int}}$. Since a theoretical crystal has

only zero vibrations of atoms, therefore, it is the energy of zero vibrations.

Accordingly, we obtain the following conclusion: the volume of a theoretical crystal (tribosystem) with zero atomic vibrations has the same internal energy density $u_{MQ_{int}}$ as the extremely deformed critical friction volume (distorted by defects in the crystal structure of the limiting density) with accumulated latent (potential) energy $u_e^* = \Delta H_S$.

This fact additionally confirms the validity of the thermodynamic theory of strength [4]. The accumulated critical density of internal energy of defects (structural distortions (static and dynamic)) in the local volume responsible for the destruction is a universal constant of the state of the material, because it is at the same time the internal energy of an ideal crystal, which is indisputably a constant.

The energy of an atom at its zero equilibrium oscillations is half the kinetic energy and half the potential energy. Thus, it can be argued that during the formation of defects in the crystal structure, there is a redistribution (transformation) of the internal energy of the crystal to the defect area.

This fact absolutely accurately confirms the basic logic of the structural and energy interpretation of Professor V.V. Fedorov's strength concept [4], according to which the work of external forces is spent on breaking the interatomic bonds of the crystal lattice, i.e. on the formation of defects in the crystal structure.

Here it is quite possible to recall the following conclusion from the monograph [5]: "Thus, there is a fundamental difference between two fundamental concepts: the activation energy of the elementary act of breaking the interatomic bond and the energy of bond rupture (vacancy formation). The activation energy of breaking an interatomic bond should be understood as the work that must be spent reversibly and isothermically in order to transfer an atom to an activated (unstable) state [5]. As noted, this energy is equal to $U = D_0/4$. If a lower energy U is supplied to the atomic bond, then the bond will not be broken. If an equal (or somewhat greater) energy U is applied to the connection, then the connection enters an unstable state capable of rupture. In this case, the bond is broken by "pumping" elastic energy from neighboring, surrounding bonds. The amount of this energy varies within limits $0{,}25D_0 > \Delta W \geq D_0$ and depends on the structure of the material and the type of crystal lattice." Here ΔW – the irreversible work spent on breaking the atomic bond; D_0 – the energy of bond dissociation.

Now let's determine the amount of energy U_{atom} per atom of a mechanical quantum. A mechanical quantum, as a transcendental quantity, contains 8,103... atoms. Thus,

$$U_{atom} = \frac{U_{MQ}}{8103} = \frac{2{,}032 \cdot 10^{-15}}{8103} =$$

$$= 2{,}468 \cdot 10^{-19} J = 1{,}54 \text{eV}. \qquad (16)$$

The monograph by A. N. Orlov and Yu.V. Trushin [7] provides experimental data [8,9] on the energy of vacancy formation. For $\alpha - Fe$ is $1{,}4\text{eV}$ and $1{,}5\text{eV}$; for $\gamma - Fe$, respectively $1{,}7\text{eV}$, and $1{,}5\text{eV}$; for $\delta - Fe - 1{,}5\text{eV}$. The average energy of vacancy formation is equal here $1{,}52\text{eV}$.

As can be seen, the discrepancy with the value calculated above $U_{atom} = 1{,}54\,\text{eV}$, which is the energy of bond rupture (vacancy), is

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

A very convincing result.

7. ON THE THERMODYNAMICS OF THE IDEAL STATE OF A TRIBOSYSTEM

Considering the above-mentioned principle of symmetry of the ideal evolution of tribocontact (elementary tribosystem), we actually see

(Figure 3) that the process begins and ends in the regions of pure elasticity.

In conditions of complete (ideal) equilibrium at point 4 (see Figure 3), the system has a loss of one mechanical quantum (one particle of the system). Here we have a state of pure (structurally dispersed) elasticity under plastic deformation. This is a state of structural superplasticity [3] and abnormally low friction.

On the other hand, this is minimal reversibility, i.e. elasticity (initial at static contact) under conditions preceding plastic deformation. The first is the final state of contact evolution (Figure 3). The second is the initial state of its evolution (Figure 3).

These two disparaging little things are equal to each other. Thus, the minimum loss of one mechanical quantum is equivalent to the initial net elasticity, i.e. reversibility. Therefore, adding one nano-quantum to the system, as well as removing it, has an effect equivalent to pure elasticity (reversibility).

Consequently, the work of such an absolutely elastic effect is zero. Now let's compare this conclusion with the formulation of the chemical potential, which states that the chemical potential is the energy of adding (removing) one particle into the system without performing work.

At the beginning of the evolution of the tribosystem, we add to the process of plastic deformation from the static (initial state) a small reversible component of pure elasticity $\mu = \mu_{elast}$, and at the end of the ideal (most complete) evolution of the contact ($\mu_{dis} = 1{,}0$) we return to the state of pure elasticity of the entire contact in dynamics with the loss (return) of the smallest particle of a material solid (deformable system) – one a mechanical (nano) quantum.

Thus, to a deformable solid body system (contact), we can equilibriously and reversibly add (take away) a certain small amount of matter energy (one particle) without performing work. This is true, since we are talking about pure elasticity.

Let's compare this conclusion with the formulation of a chemical potential about adding (removing) one particle to a system without performing work. Let's consider how the state of maximum dissipativity (Figure 3) of the tribosystem at point 4 (equilibrium far from the equilibrium state) corresponds to the *J.W.*Gibbs equation for equilibrium processes [4,10].

Let's take one particle (an ideal crystal) of a system with an internal energy $U_{MQ_{int}}$ equal to the energy of one nano-quantum U_{MQ} and multiply it by the number N_{MQ} of such particles in the volume of an elementary tribosystem (equilibrium friction contact).

We obtain the internal energy E of the system in its initial (before deformation) state:

$$E = U_{MQ_{int}} \cdot N_{MQ}. \qquad (17)$$

Now we will perform work $\mu_* Nl$ on the system, which will lead to a change in the internal energy of the system by an amount ΔU_e^* (section 0-2 in Figure 3).

Next, we release the accumulated energy ΔU_e^* in the form of the energy of the thermal effect $\vec{Q} = TS$ (in this case, dynamic dissipation) (section 2-4 in Figure 3), which reversibly returns the system to its original (elastic) state (but in a new structural form). With that said, we write (17) as:

$$E + \mu_* Nl - TS = U_{MQ_{int}} \cdot N_{MQ} \qquad (18)$$

or

$$E + \Delta U_e^* - \vec{Q} = U_{MQ_{int}} \cdot N_{MQ}\,. \qquad (19)$$

As a result, we obtain the ratio

$$U_{MQ_{int}} = \frac{E + \Delta U_e^* - \vec{Q}}{N_{MQ}} = \frac{E + \mu^* Nl - TS}{N_{MQ}} =$$

$$= \frac{E}{N_{MQ}} = \frac{G}{N_{MQ}} = \mu_{chem}, \qquad (20)$$

which is known as the ratio μ_{chem} for the chemical potential.

Actually, here we get that the energy of one mechanical quantum is a chemical potential. The internal energy of an ideal (initial) system E (its inheritance) is equal to the critical accumulated internal (free) energy ΔU_e^*, the total heat of melting ΔH_S (in the liquid state at the melting point) and, consequently, the J.W.Gibbs potential G:

$$E = \Delta U_e^* = \Delta H_S = G. \qquad (21)$$

On the other hand, if there is an infinitesimal amount of matter (mass) dm multiply by the unit of energy attributed to this mass $\frac{dU}{dm}$, we get an infinitesimal increment of the internal energy dU of the system, which can be added (taken away) when adding (subtracting) a small amount of matter:

$$\frac{dU}{dm} dm = dU. \qquad (22)$$

Now, if we perform an infinitesimal amount of external forces PdV on the system (contact) and reversibly return it as an infinitesimal thermal effect TdS we can write the following:

$$\frac{dU}{dm} dm + Pdv - Tds = dU. \qquad (23)$$

Let's denote the ratio $\frac{dU}{dm}$ by the parameter μ_{chem} and write the ratio (23) as

$$\mu_{chem} dm + PdV - Tds = dU. \qquad (24)$$

As a result, we obtain the J. Gibbs equation in differential form for the case of an equilibrium, reversible process with the addition of such a small amount dm of matter that S and V remain constant $(dS = dV = 0)$. Here, the value –

$$\mu_{chem} = \left(\frac{dU}{dm}\right)_{S,V} = U_{MQ_{int}}, \qquad (25)$$

is known as the chemical potential.

Thus, the analysis of the ideal evolution of an elementary tribosystem (friction contact) shows that the energy interpretation of the friction process corresponds to the well-known equation of J. Gibbs, obtained by him for equilibrium processes. However, there is some uncertainty about the interpretation of the J. Gibbs equation by different sources from the standpoint of the concept of chemical potential either as the energy of a small amount of added substance or as the energy of an added particle.

As the logic of structuring the elementary volume of friction into mechanical (nano) quanta and our calculations shows, such duality is quite possible. On the one hand, the chemical potential can be considered as the chemical bonding energy of a pair of crystal atoms and, as can be seen (16), there is a good correspondence in determining the bond breaking energy for iron (steel). On the other hand, a chemical potential can be called an energy attributed to a single mechanical quantum, because it is really a particle (an elementary supranatomic structure).

The analysis of the patterns of evolution of the tribosystem (friction contact) and its structural transformation to a set of the smallest particles of a material solid – mechanical quanta, rather than to a set of the smallest particles of matter – atoms, inclines the author of the article to interpret J. Gibbs energy as energy attributed to a single mechanical quantum.

Nevertheless, both opinions seem to be valid, because the concept of the thermal effect, as a general consequence of the work of deformation, according to the initial scheme (Figure 1) of the energy balance of the plastic deformation process [4], includes two components – the kinetic component of internal energy Δu_T and heat transfer energy $\vec{q}$.

Accordingly, here the first Δu_T is the energy of static (slow) dissipation of friction (atomic mechanism), and the second $\vec{q}$ is the energy of heat transfer, which is the energy of dynamic (fast) dissipation of friction by the mechanism of oscillation of mechanical (nano) quanta [1-3]. Both the first and second mechanisms of heat energy dissipation are nothing more than the mechanical energy of small particles, and according to J. Gibbs, the laws of heat are the result of a huge number of independent mechanical systems.

8. ON THE MECHANICAL QUANTUM AS A CHARACTERISTIC OF THE HEREDITARY PROPERTIES OF A DEFORMABLE SOLID

It is shown above that J. Gibbs' cell is adequately interpreted by the concept of a mechanical (nano) quantum in its physical meaning. The Gibbs cell or mechanical quantum has internal and surface energies that are equal to each other. Accordingly, the J. Gibbs potential and the energy of the mechanical quantum are constants for each solid. The densities of these energies are indeed real characteristics of hereditary properties, because they are equal to the constant of a solid body – the critical energy density of the limiting state of the local volume responsible for destruction [4].

Indeed, every material in its ideal state already knows its limiting state before ($t=0$) the beginning of the deformation process.

The correlation of these energy parameters with the vacancy energy of metallic materials is an additional confirmation of the above statement.

9. ON THE EQUALITY OF THE SURFACE ENERGY OF A MECHANICAL QUANTUM OF ITS INTERNAL ENERGY

In order to maintain the integrity of the mechanical quantum (8103, ... atoms) and its internal energy, the surface energy of the mechanical quantum (and the surface tension forces) must be at least equal to its internal energy.

In this case, the logic is clear – if the resulting crystal of a mechanical quantum has a size smaller than the nominal one (8103, ... atoms), then its surface energy is unable to maintain its integrity, and it disintegrates into atoms.... Here there is a complete analogy with D.K. Chernov's crystalline nuclei (crystallization centers) in metallurgy [11]. Such stable, growth-capable, crystalline nuclei are called critical.

If, however, the resulting crystal of the mechanical quantum has reached a size equal to the nominal size of the mechanical quantum (8103, ...) or more, then it is capable of growing and retaining its crystalline volume. In this case, its internal elastic energy on interatomic bonds is sufficient for its bulk crystalline integrity.

10. THE VERSATILITY OF THE MECHANICAL QUANTUM, THE ELEMENTARY NANOSTRUCTURE OF MATERIAL BODIES, AND THE INTERDISCIPLINARITY OF FRICTION

The dimensional universality of the mechanical quantum, which inherits the transcendental properties of the constant of the material world of number e, determines the multiple images of its manifestation, namely:

1. A mechanical quantum is the smallest particle of a material solid body.
2. A mechanical quantum is an attractor of the type of limiting cycle of plastic deformation of a solid.
3. A mechanical quantum is an elementary nanostructure.
4. A mechanical quantum is a macromolecule of a solid body.
5. A mechanical quantum is an embryo (center of crystallization) during the formation of a massive solid.
6. A mechanical quantum is an elementary tribosubsystem.
7. A mechanical quantum is a fractal of a solid body.

8. The mechanical quantum is a J. Gibbs cell.
9. A mechanical quantum is an energy carrier of a chemical potential.
10. A mechanical quantum is an elementary theoretical crystal.
11. A mechanical quantum is an elementary nanocircuit.
12. The mechanical quantum is a standard for the wear of solids.
13. A mechanical quantum is a quantitative characteristic (constant) of the hereditary energy properties of solids.
14. A mechanical quantum is a nanodiamond.

Such a multiplicity of the mechanical (nano) quantum of friction is not unusual. This property of the mechanical quantum confirms the essence of the global phenomenon of nature – friction and substantiates the validity of the modern interdisciplinary approach to the study of this phenomenon.

11. ON THE TRANSCENDENCE OF THE MECHANICAL QUANTUM OF DISSIPATIVE FRICTION STRUCTURES AND ITS SURVIVABILITY

We note one very significant property of the calculated mechanical quantum. The limiting (minimum) nanostructure of a solid deformable body of 8103, ... atoms is determined by the limiting, transcendental number e [1]. On the one hand, this fact confirms the validity of the theoretical model for analyzing the limiting structural state of a deformable solid. On the one hand, this fact confirms the validity of the theoretical model for analyzing the limiting structural state of a deformable solid. Here, the mechanical quantum is the limit cycle attractor for the plastic deformation process. On the other hand, this transcendent number of atoms forming an elementary nanostructure determines a high degree of its stability (survivability), namely, as elementary (nano) structures, because it assumes the existence of a wide dimensional spectrum of these structures in the vicinity of the size of the transcendental number of a mechanical quantum equal to $W_{TS}^{3} = e^{9} = 8103{,}0855....$ (here W is the probability of the state of the mechanical quantum) [1].

These nanostructures can have dimensions close to transcendental - 8101, 8102, 8103, 8104, 8105 and so on. The transcendent dimensional nature of the mechanical quantum determines the effect of the constant striving of nanostructures of a solid body to achieve a transcendental value both individually and in an array of these nano-structures. However, this is not possible, but it is their theoretical "fate". This fact determines, as it were, the global "survivability" of a mechanical quantum. At the same time, this fact determines the tendency of nanoparticles to hierarchical, clustered (granular) agglomeration in an attempt to achieve an average, transcendental value of their combined set.

12. ON THE CRITERION DENSITY OF INTERNAL AND SURFACE ENERGIES OF A MECHANICAL QUANTUM

The theoretical and computational analysis of the energy potentials of the elementary tribosystem (critical friction volume) and the elementary nano-structure of the mechanical quantum showed that the values of the internal $U_{MQ_{int}}$ and surface energy $U_{MQ_{sur}}$ of the mechanical quantum as an ideal theoretical crystal of atomic spherical shape are equal.

The internal energy density of a mechanical quantum is equal to the internal energy density of an extremely deformed volume of an elementary tribosystem. It is concluded that an ideal theoretical crystal of a mechanical quantum possesses the internal energy of hereditary properties that determine the limiting state of a given material. Accordingly, the surface energy density of this ideal atomic-spherical crystal also has a critical value that determines the limiting state for rupture of the structure with the formation of a crack (gap) [12]. Therefore, there is a direct correlation between the Griffiths-Irwin-Orowan surface

energy crack formation and the additive internal energy constant, the density of accumulated internal fracture energy according to V.V.Fedorov [4-6].

This relationship is confirmed by equation, obtained in the framework of the general ergodynamics of deformable bodies by V.V.Fedorov [6]:

$$\gamma_{эф} = \frac{3\pi}{1+\mu'} a_0 \, u_{e^*} \, . \qquad (26)$$

Here a_0 is the parameter of the crystal lattice; μ' - the coefficient of transverse deformation.

Let's perform the following analysis and calculation. Let's write down the expression for the density of internal energy u_{e^*} in the volume V_{MQ} of a mechanical quantum:

$$u_{e^*} = \frac{U_{MQ_{int}}}{V_{MQ}} = \frac{6\,U_{MQ_{int}}}{\pi\, D_{MQ}^3}. \qquad (27)$$

Here, V_{MQ} the volume of a spherical ball of a mechanical quantum is –

$$V_{MQ} = \frac{4}{3}\pi\, R_{MQ}^3 = \frac{\pi\, D_{MQ}^3}{6}. \qquad (28)$$

The area of the spherical surface of the ball of a mechanical quantum is equal to –

$$P_{MQ} = 4\pi\, R_{MQ}^2 = \pi\, D_{MQ}^2 . \qquad (29)$$

Accordingly, the surface energy density of a mechanical quantum is

$$\gamma_* = \frac{U_{MQ_{surf}}}{\pi\, D_{MQ}^2} = \frac{U_{MQ_{int}}}{\pi\, D_{MQ}^2}. \qquad (30)$$

Let's make an additional transformation for the ratio (27) of the internal energy density u_{e^*} of a mechanical quantum:

$$u_{e^*} = \frac{U_{MQ_{int}}}{V_{MQ}} = \frac{6\,U_{MQ_{int}}}{\pi\, D_{MQ}^3} =$$

$$= \frac{6}{D_{MQ}} \cdot \frac{U_{MQ_{int}}}{\pi\, D_{MQ}^2}. \qquad (31)$$

In the obtained ratio (31) for the internal energy density of the mechanical quantum, we see the presence of the surface energy density of the mechanical quantum (30).

Therefore, we can write the ratio for the energy densities of a mechanical quantum in the form –

$$u_{e^*} = \frac{6\,\gamma_*}{D_{MQ}} \qquad (32)$$

or

$$\gamma_* = \frac{D_{MQ}\, u_{e^*}}{6}. \qquad (33)$$

It follows from relation (24) that the density of the surface energy of a mechanical quantum is a part of the density of the internal potential energy of a mechanical quantum. Let's perform a number of calculations. We know the amount of energy $U_{MQ} = 2{,}032 \cdot 10^{-15} J$ (for steel) dissipated by one mechanical quantum as a result of the complete evolution of the elementary tribosystem. The volume of a mechanical quantum is –

$$V_{MQ} = \frac{4}{3}\pi\, R_{MQ}^3 = \frac{\pi\, D_{MQ}^3}{6} =$$

$$= \frac{3{,}14 \cdot (7{,}177 \cdot 10^{-9})^3}{6} = 193{,}467 \cdot 10^{-27} m^3 .$$

Hence, the internal energy density of a mechanical quantum is -

$$u_{e^*} = \frac{U_{MQ_{int}}}{V_{MQ}} = \frac{2{,}032 \cdot 10^{-15}}{193{,}467 \cdot 10^{-27}} =$$

$$= 0{,}010503 \cdot 10^{12} \frac{J}{m^3} =$$

$$= 10{,}503 \cdot 10^{9} \frac{J}{m^3} = 10{,}5 \frac{J}{mm^3} .$$

This value coincides with the value of the critical internal energy density (melting enthalpy ΔH_S [4]) for steel.

Now let's determine the surface energy density of a mechanical quantum. Here, the surface area of the mechanical quantum is –

$$P_{MQ} = \pi D_{MQ}^2 = 3{,}14 \cdot (7{,}177 \cdot 10^{-9})^2 =$$

$$= 161{,}739 \cdot 10^{-18} m^2 .$$

Accordingly, we get –

$$\gamma_* = \frac{U_{MQ_{surf}}}{\pi D_{MQ}^2} = \frac{U_{MQ_{int}}}{\pi D_{MQ}^2} =$$

$$= \frac{2{,}032 \cdot 10^{-15}}{161{,}739 \cdot 10^{-18}} = 12{,}56 \frac{J}{m^2} .$$

Thus, when the surface and internal energies of a mechanical quantum are equal, their energy densities differ greatly. The surface of the mechanical quantum accounts for $12{,}56\ J$, the volume of the mechanical quantum accounts for $10{,}503 \cdot 10^9 J$.

Practically, it can be assumed that the surface energy density of a mechanical quantum is an insignificant part of the internal energy density of a mechanical quantum and can be ignored. Although, on the other hand, these are incomparable values.

Here we have a complete correspondence with the equations of the theory of continuous media [12] by L.I. Sedov. The main Griffith relation of crack theory [12] is related to the internal energy (additive constant internal energy (fracture energy)), which actually complements the equations of elasticity theory. Therefore, V.V. Fedorov's strength criterion [4-6] about the critical density of internal energy u_{e*} in the local volume responsible for fracture is at the same time a criterion for crack development.

13. TO THE MECHANISM OF ABNORMALLY LOW FRICTION OF A PERFECTLY STRUCTURED THIRD BODY

In the mechanism of mutual oscillation of mechanical quanta, during the ideal evolution of the friction contact, surface forces, generalized by the nature of surface energy, take the main part. In this state, the third body [3] implements the effect of structural superplasticity (Figure 5).

Is it worth trying to strictly understand and explain the mechanism of mutual oscillatory rotation of mechanical quanta? I don't think that's necessary.

Here it is possible to refer to the Tomlinson model of surface repulsive forces [13,14] assuming that this model clearly hints at a pattern of alternating rupture and formation of molecular bonds without loss.

On the other hand, for example, we can take the situation with Rayleigh-Benard cells in a highly heated liquid. We know that they are there, we can visually observe them, and that's enough for us!

Additionally, a number of fundamental calculations have been proposed above, substantiating some fundamental relationships in energy concepts.

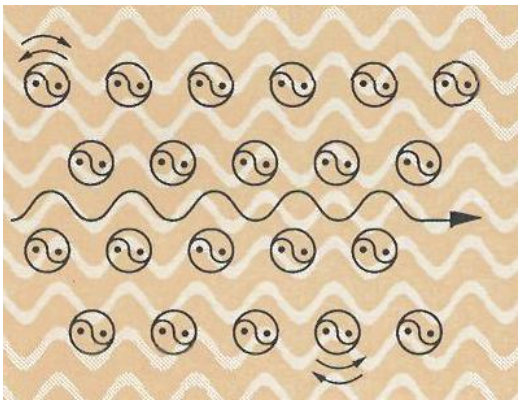

Figure 5. Nano-quantum structure of the "third body" in the ideal evolution of the friction contact [2,3]

Apparently, on the surfaces of mutually and rotationally oscillating mechanical quanta, there is an absolutely balanced state similar to the balanced internal state of mechanical quanta in volume and precisely as theoretical (ideal) crystals. Therefore, a model of ideal and minimal friction or their repulsion is implemented on the surfaces of mutual sliding of mechanical quanta [15].

It is quite possible that under the conditions of an ideal structural arrangement of the third body by mechanical (nano) quanta, a model of

superfluidity can be assumed by the mechanism of ideal sliding. There are suggestions that the temperature can reach absolute zero in the volume of dynamic dissipative friction structures.

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. In this case, all mechanical quanta, with the exception of one, reversibly elastically transform (dampen) the energy of external mechanical motion. Actually, a loss of one mechanical quantum for the ideal evolution of an elementary tribosystem (friction contact) can explain the fundamental irreversibility of the process and at the same time maximum equilibrium and maximum reversibility (ideality).

By analogy with classical quantum theory, we can say that in this case the system (tribosystem) is in the ground state (here, as it were, all mechanical quanta are directed against the field) - the tribosystem cannot give energy to any other system (the external environment) simply because it (tribosystem) does not accumulate energy in this state. In this case, the tribosystem is in almost perfect equilibrium with the environment.

The Tomlinson model can be supplemented with the mechanical quantum model discussed above, namely, solid state macromolecules and J. Gibbs crystals. The surface energy of a mechanical quantum, like free surface energy, is the Gibbs surface energy.

It is well known that the J.W. Gibbs cell represents a small part of the energy that can be reversibly added to the system and reversibly taken away from the system without performing work. The work of the interaction of such mechanical quanta is reversible, and in this we can again refer to Tomlinson's work on the reversible and elastic interaction of molecules of friction surfaces by the effect of their elastic repulsion.

In other words, in the model of superplasticity (superfluidity) of the third body, we can have an ideally elastic and reversible process of alternating interaction of molecules (mechanical quanta) without energy costs and losses.

Actually, this makes the transformation cycle at the friction contact the most complete, similar to the ideal (almost reversible) thermodynamic L. Carnot cycle.

The word «almost» here concretizes this cycle with the loss of one mechanical quantum out of about 63 million quanta involved in the operation of an ideal dynamically dissipative friction structure.

In the most general case, such a state of friction contact should be interpreted as a state of self-organized nano-quantum solid lubricant [16].

14. CONCLUSIONS

The free energy E of the initial, before deformation, theoretical crystal with the size V_f^* of an elementary tribological system [17] is equal to: the maximum accumulated internal potential energy $\Delta U_e^* = V_f^* u_e^*$ of various kinds of elementary defects and damages to the structure of the crystal lattice of an elementary tribosystem; the total enthalpy ΔH_S of melting (in the liquid state at the melting point); scattered (previously accumulated critical potential energy ΔU_e^*), to newly formed structural elements (grains) – mechanical quanta, in the form of elastic surface energy $\vec{Q}^* = V_f^* \vec{q}_* = V_f^* u_e^*$, during the complete evolution of the elementary tribosystem.

The internal free energy $E' = U_{MQint} \cdot N_{MQ}$ of a set of mechanical quanta in a volume V_f^* of a structurally adapted elementary tribosystem is equal to ***the hereditary free energy*** E of the initial (before deformation) theoretical crystal

with the size of an elementary tribological system.

During friction, as a result of the structural-energy evolution of the deformable contact, all the limiting energy states are constant and equal to each other. Deformable solids in their evolution have initial ***hereditary*** *energy states*, which are ***constants*** and remain unchanged during the transition from one limiting structural state of friction contact to another.

The ideal evolution of a tribological contact can have a practical complete reversible evolutionary cycle (maximum efficiency), which is similar to the complete reversible thermodynamic L. Carnot cycle, but with minimal irreversibility in the form of the loss of one mechanical quantum, which is equal to pure elastic reversibility, which begins the process of elastic-plastic deformation.

The state of maximum efficiency of tribocontact (abnormally low friction) is a state of self-organized solid lubricant [16], an ideally structurally organized «third body», the behavior of which can be identified by the Tomlinson model of surface repulsive forces (Rayleigh-Benard cells) and the mechanical quantum model supplemented above, namely, solid macromolecules and J. W. Gibbs crystals.

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