Synergy and Self-organization in Tribosystem’s evolution. 
Energy Model of Friction.

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Abstract: Different approaches are known to treat self-organization in tribosystems, related to the structural adaptation in the formation of dissipative surface structures and of frictional or tribo-films, using of synergistic modifying of layers and coatings, e.g. of the selective material transfer during friction, etc. Regarding tribological processes in contact systems, self-organization is observed as spontaneous creation of higher ordered structures during the contact interaction. The proposed paper considers friction as process of transformation and dissipation of energy and process of elasto-plastic deformation localized in thin surface layers of the interacting bodies. Energetic interpretation of friction is proposed. Based on the energy balance equations of friction, the evolution of tribosystems is followed in its adaptive-dissipative character. It reflects the variable friction surfaces compatibility and the nonlinear dynamics of friction evolution. Structural-energy relationships in the contacting surfaces evolution are obtained. Maximum of tribosystem’s efficiency during the evolution is the stage of self-organization of the friction surface layers, which is a state of abnormal low friction and wear.

Keywords: friction, energy, adaptation, dissipation, synergy and self-organization

1. Introduction

Friction is a global natural phenomenon of transformation and dissipation of the energy of external relative motion. Friction strictly obeys the energy balance equations. In the most general case it shows an adaptive-dissipative character. The deformable contact body evolves and adapts over time during friction showing well-defined stages in the evolution. Most characteristic is the property of self-organization [1], which is closely related to the synergy, i.e. the common mutual activities of the equilibrium states. When starting a self-organization process, the macro-synergy of the two opposite balance tendencies in the energy transformation, changes in an exclusive nano-synergy of frictional contact subsystems’ states with properties of an attractor.

2. Thermodynamic analysis of friction process

Being a global phenomenon in nature, friction firmly obeys energy balance equations (figure 1). In terms of thermodynamics [2-4], friction results of two simultaneous interrelated and opposite
tendencies: on the one hand, storage of the latent (potential) energy $\Delta U_e$ of various defects and structure damages in the contact volumes and, on the other hand, release (dissipation) of that energy $Q$ due to various relaxation processes. The first trend defines the effect of deformation strengthening and integrally characterizes damage and fracture (a state parameter). The second trend defines the heat effect of friction; it is responsible for the quasi-viscous component of the process.

\[ \omega_f = \Delta U_e + q \]

\[ \dot{\omega}_f = \dot{u}_e + \dot{q} \]

\[ W_f = \Delta U_{e_1} + Q = \Delta U_{e_1} + \Delta U_{e_2} \]

\[ F_f = \frac{\Delta U_e}{l} + \frac{Q}{l} = \frac{\Delta U_{e_1} + \Delta U_{e_2} + Q + Q_2}{l} \]
\[ F_v = \frac{\dot{U}_1 + \dot{U}_2 + \dot{Q}_1 + \dot{Q}_2}{v} = F_{\text{mechanical}} + F_{\text{molecular}} \tag{7} \]
\[ \mu = \frac{\Delta U_{\epsilon_1} + \Delta U_{\epsilon_2} + Q + \dot{Q}}{Nl} = \mu_{\text{adapt}} + \mu_{\text{dis}} = \mu_{\text{adapt}} + \mu_{T(\text{dis})} + \mu_{Q(\text{dis})} \tag{8} \]
\[ \mu_v = \frac{\dot{U}_1 + \dot{U}_2 + \dot{Q}_1 + \dot{Q}_2}{Nv} = \mu_{\text{deformation}} + \mu_{\text{adhesion}} \tag{9} \]

Here \( \mu \) is the friction coefficient; \( \mu_{\text{adapt}} \) - the adaptive friction coefficient (of Amonton’s Law); \( \mu_{T(\text{dis})} \) and \( \mu_{Q(\text{dis})} \) - static and dynamic components of dissipative friction coefficient \( \mu_{\text{dis}} \); \( \Delta U_{\epsilon} = \Delta u_{\epsilon} \cdot V_f \), \( \Delta U_T \) - potential and heat components of internal energy; \( \dot{U}_{\epsilon} = \dot{u}_{\epsilon} \cdot V_f \), \( \Delta U_T \) - rates of change of the potential and heat components of internal energy; \( Q, \dot{Q} \) - heat effect of friction and friction power, i.e.: \( Q = \Delta U_{\epsilon_1} + \dot{Q} \), \( \dot{Q} = \dot{U}_{\epsilon_1} + \dot{Q} \); \( \dot{Q}, \dot{\dot{Q}} \) - heat effect of the dynamic dissipation and its power; \( V_f \) - friction volume; \( N \) - normal load; \( l \) - friction way. The density of hidden energy \( \Delta u_{\epsilon} \) is an integral parameter of the tribo-state and fracture ability (of destruction \( \Delta u^* \) [3, 4]). Indices in equations (6) – (9) identify the friction parameters in time unit \( v \) and friction way \( l \).

The correlations between energy balance components \( \Delta u_{\epsilon_1} \) and \( \Delta u_{\epsilon_2} \), \( \Delta u_T \) and \( \Delta u_T \), as well as \( \dot{Q}_1 \) and \( \dot{Q}_2 \) in equations (1) - (9) of the friction process vary widely depending on the physico-chemical properties and structure of contacting bodies materials, and on the friction conditions. The diversity of value ratios in the energy balance components actually determines the whole variety of particular (limit) displays of friction process [5, 6].

For the particular case of friction localization in third body volume (zone of compatibility (see below figure 6)), the equations (4) and (5) transform in:
\[ W_T = \Delta U_{\epsilon_1} + Q_3 \tag{10} \]
\[ W_T = \dot{U}_{\epsilon_1} + \dot{Q}_3 \tag{11} \]
This way of recording the energy balance equations during friction is not inconsistent with above considerations, but complements them and has a larger physical validity. Here the index 3 marks energy balance components for the case of friction in the third body volume (the secondary structures), which are analogous to equations (4) and (5).

Thus, the thermodynamic analysis of the processes of plastic deformation and destruction of solid body contact volume allows us to get generalized (binomial) dependencies for friction.

3. Energetic interpretation of friction coefficient

For the case of low speed slip and small heat effect of friction \( (Q \simeq 0) \) energy balance equation (8) gives the Amontons’ friction coefficient in a generalized form, as follows:
\[ \mu = \frac{F}{N} = \frac{\Delta U_{\epsilon}}{Nl} ; \quad F = \frac{\Delta U_{\epsilon}}{l} ; \quad Q \simeq 0 . \tag{12} \]
So, the friction coefficient of Leonardo da Vinci (G. Amontons) has a deep physical meaning. On the one hand, this is a parameter characterizing in general terms the resistance to the relative displacement (movement) of the surfaces, because it reflects the fraction of external motion energy that is "destroyed" by friction in the form of stored (potential) hidden energy $\Delta U_e$. On the other hand, this is a generalized characteristic of the damageability, because the coefficient of friction is determined by the density of the latent energy $\Delta U_e$ characterizing the degree of defectiveness of the structure and being a generalized parameter of damageability [3, 4]. Here we can also say that the coefficient of friction uniquely reflects in general terms the structural perfection (imperfection) of the deformable contact volume [2, 3], because the parameter $\Delta U_e (\Delta U_e)$ is determined by the energy of different types of defects and damages, being generalized characteristic of structure (structure parameter) in accordance with the main conclusion of the thermodynamic theory of strength [3].

4. Generalized experimental friction curves

The dependences obtained for the friction coefficient $\mu$ are in agreement with the experimental curves $\mu = \mu(N,v)$ (figures 3-5).

![Figure 3. P. Conti’s experimental results [7]](image-url)
A subsequent analysis of modern experimental data using equations (1)-(12) has shown [2] that the experimental friction curves (figures 3-5) of type \( \mu = \mu(N,v) \) are generalized friction curves that reflect the evolution (the change in the friction coefficient) of the tribosystem.

5. Regularities of tribosystems’ evolution

Tribosystem’s evolution given as a diagram (figure 6) is of adaptive-dissipative character (1)-(9) and reflects the competitive (dialectical) nature of friction. The evolution curve has a number of principal points (1,2,3,4,5) of the transient stages of the tribosystem, which firmly obey the balance principle of friction. Between these points are located the most characteristic areas of tribosystem’s behavior that reflect the general properties of its nonlinear dynamics.

So, we can see the following conditionally marked points and stages: 0-1 - section of static friction and deformation strengthening; 1 - limit deformation strengthening point; 1-2 – stage of pumping of excessive energy; 2 – point of seizure and transition from external to internal friction (critical non-stability); 2-3 – stage of dissipative structures formation (formation of heat fluctuation in friction volume); 3 – minimum compatibility point; 1-2-3 – self-organization area; 3-41 – stage of compatibility; 4 - point of wearlessness (abnormal low friction); 5 – point of heat seizure.
Figure 6. Structural-energy diagram of frictional surfaces evolution [2]. Designation on the axes:

\(N, v\) - load and speed. \(\mu_{st}, \mu_{dyn}, \mu_{elast}, \mu_{pl}\) - static, dynamic, elastic, plastic friction coefficients;

\(T_f, T_S\) - the flash point in the friction contact volume in point 3 and the melting temperature.

The ideal evolution of the tribosystem is symmetrical. The process begins and ends in the areas of elastic behaviour. There is a plastic maximum of friction between them (a highly-excited state) as a condition for self-organization and adaptation.

In the most general case, the patterns of evolution (adaptation) of tribosystems can be represented in the form of two stages (figure 6). First stage (0-2) – stage of density increase of the latent energy \(\Delta U_e\) up to the limit value \(\Delta U^*\) in some critical volume of friction \(V_f^*\). Second stage (2-4) – stage of the structural decomposition (transformation) into two parts of the critical volume of friction \(V_f^*\) (of the elementary tribosystem), namely: adaptive \(V_{adapt}\) and dissipative \(V_{dis}\) volumes. In the limit (point 4), this stage is characterized by a complete transformation of the adaptive critical volume \(V_{adapt}^*\) into dissipative volume \(V_{dis}^*\).

Above volumes characterize different relationships of energy transformation of the external mechanical motion during friction. The adaptive volume \(V_{adapt}\) is related to an irreversible absorption of deformation energy. Latent energy of deformation \(\Delta U_e\) is accumulated in this volume, and then centers of fracture emerge. The dissipative volume \(V_{dis}\) is capable of reversible transforming (dissipation) the energy of the external motion. It does not accumulate latent energy of deformation due to a process of reversible elastic-viscoplastic deformation.
The proposed theoretical and calculated assessments [2] showed that the dissipative volume of friction produces a reversible elastic transformation of the energy of external mechanical motion with a density $\tilde{q}^*$ equal to the critical density of the latent energy $u^*_e$.

The culmination of tribosystem’s evolution is its final and limiting state, point 4 – the state of abnormal low friction and wearlessness (state of maximal performance and functional ability).

It has been shown [2] that the value of the minimum adaptive volume of friction $V^\text{min}_{\text{adapt}}$ corresponding to zero value of the plastic friction component $\mu^\text{min}_{\text{adapt}} = \mu^\text{clast}$ is not equal to zero, but is equal to the size of some minimal structural element of the deformable solid body.

It is of scientific interest to analyze this minimal structural composition during friction in the aspect of the general phenomenon of adaptation due to self-organization.

6. Structural-energy and physical patterns of self-organization and synergy

![Figure 7](image)

Figure 7. (a) Friction coefficient $\mu$ versus load [8], and (b) friction power $W_f$ (solid line) and parameter $N \cdot \nu$ (dash line) versus load for the couple Nylon 6 – steel [2]: $I - \nu = 1 \text{ m/s}$; $II - 0.6$; $III - 0.3$; $IV - \nu = 0.1 \text{ m/s}$

An analysis of the laws of self-organization during friction will be carried out taking into account the equations of the energy balance of friction (1)-(11), the energy interpretation of friction coefficient (12), and the existence of generalized experimental friction curves (figures 3-5). It is particularly important to rearrange [2] the Wanatabe’s [8] curve (figure 4) to the curves form of friction power $W_f$ and external forces power $N \cdot \nu$ (figure 7). The curve in figure 4 is rearranged to three curves (figure 7). The first diagram (figure 7a) shows the friction coefficient versus load at different speeds;
horizontal line is given that crosses the friction coefficients curves at a unit value. Points 1 and 3 are denoted on the ascending and descending branches of these curves. The maximum of friction curves are points 2. Figure 7b shows that at points 1 and 3 there is an intersection of the friction work (power) $W_f$ curves and the parameter $Nv$, which is the work (power) of external forces. Accordingly, between these points there is an excess of the values of friction powers $W_f$ over the values of the work of external forces $Nv$. After points 3, on the contrary, the values of the friction power $W_f$ are lower than the values of the $Nv$ parameter.

Section 0-1 (figure 6) – preparatory (initial) stage. It is characterized by dislocation mechanism of plastic deformation, formation of the critical volume of friction $V_f^*$ and accumulation of energy of dislocation strengthening of the limiting value $\Delta U_{eD}^*$. The process of accumulation of latent (potential) energy of defects is miscoordinated with the process of its release. Up to point 1, the accumulated energy of friction is dissipated after wear particle detachment from the volume of the friction surface, i.e. there is no cooperative action or synergy.

Point 1 - the point of equilibrium. The friction coefficient has a balance value equal to unit (see figures 6, 7). At point 1, the possibilities of plastic deformation according to the dislocation mechanism are exhausted; a critical volume of friction $V_f^*$ is formed in point 1. This is the smallest contact volume that has accumulated the density of dislocations energy $\Delta U_e = \Delta U_e^* = \Delta U_{eD}^*$. In fact, the volume of the elementary tribosystem was formed, i.e. the system capable of further transforming and dynamically dissipating energy. This is the point of the limiting dislocation (deformation) strengthening of the critical volume of friction $V_f^*$. Point 1 is the starting point of self-organization.

As seen from the experiment (figures 7a and b), we have equality of the power (work) of friction $W_f$ and the power (work) of the external forces $Nv$: $W_f = \mu Nv = Nv$.

Hence we obtain the condition $\mu = \frac{W_f}{Nv} = 1,0$, which corresponds to the experimental value of friction coefficient $\mu = 1,0$ (see figure 7a).

Accordingly, the energy interpretation of the friction coefficient (12) shows: $\mu = \frac{\dot{U}_e}{Nv} = 1,0$.

At point 1, equality takes place (see figure 7b) of the work of external forces $Nv$ with the work of friction $W_f$ and the accumulated potential energy $\Delta U_{eD}^*$ of dislocation strengthening in the critical volume of friction $V_f^*$: $Nv = W_f = \Delta U_{eD}^*$.

Material Science aspect. The schematic diagram (figure 8a) shows how the critical volume of friction $V_f^*$ is covered by a grid of dislocation slip lines with dislocations on them, which form "dislocation forests", i.e. the state of limiting dislocation strengthening. Such state of the critical volume of friction $V_f^*$ can be represented by an equivalent scheme (figure 8b), which shows that only half of this volume
is filled with dislocations (being large defects, dislocations cannot fill the entire crystal lattice of the volume of friction $V_f^\ast$).

Figure 8. Schematic diagrams of potential energy $\Delta U_{e_D}^\ast$ accumulation of dislocation slip lines in the critical volume of friction $V_f^\ast$

**Synergy of the area 1-2.** The work (transformation) of the internal energy fields of the limiting dislocation strengthening $\Delta U_{e_D}^\ast$ is expended on the formation of internal energy fields of vacancies $\Delta U_{e_V}^\ast$ in the critical volume of friction $V_f^\ast$. Self-organization began, doing it certainly as a self-dependent process! At point 1, the friction volume $V_f^\ast$ possesses a stock of accumulated potential energy of dislocations $\Delta U_{e_D}^\ast$ which is capable of performing the job of vacancies creation. Actually, point 1 is the starting point of self-organization. Point 1 is in the zone of all-round, non-uniform compression $F = N$ and has the limiting reserve of accumulated energy $\Delta U_{e_D}^\ast$. But the system (figure 6) evolves further. Why? Self-organization! What does it mean? The system is further organized self-dependently.

**Mechanism of the beginning of self-organization.** At point 1, the centers of limiting deformation (dislocation) strengthening under conditions of all-round irregular compression (pressure plus shift (Bridgeman)) become sources of formation of nonequilibrium vacancies (work is done), which begin to accumulate in the regions of the crystal lattice (figure 9a), which are free from dislocations. Thus, work is done by internal forces on accumulation of energy of vacancies. Further, in the stage 1-2, the energy of vacancies $\Delta U_{e_V}^\ast$ accumulates, equal to the energy of dislocation strengthening of point 1, i.e. $\Delta U_{e_V}^\ast = \Delta U_{e_D}^\ast$.

Figure 9. Schematic diagrams of potential energy of vacations $\Delta U_{e_V}^\ast$ accumulation in crystal lattice areas free of dislocation strengthening regions of energy $\Delta U_{e_D}^\ast$ in the critical volume of friction $V_f^\ast$

**Material Science aspect.** The schematic diagram (figure 9a) shows that vacancies fill-in those places in the crystal lattice, which are free from dislocation slip lines and dislocations on them. Sources of the
vacancies become the centers of limiting deformation (dislocation). So, the work of external forces $N_v = W_f$ from point 1 and above maintains a level of constant energy density $\Delta U^*_D$ of the limiting dislocation strengthening, and the centers of deformation supersaturation (of the strengthening) pump the energy of vacancies $\Delta U^*_V$ into the regions of the crystal lattice that are free from dislocations. We have a joint action of two equal energy fields $-N_v = \Delta U^*_D$ and $\Delta U^*_D = \Delta U^*_V$. Such a state of the critical volume of friction $V_f^*$ can be represented by the equivalent scheme shown in figure 9b.

After point 1 the volume of friction $V_f^*$ becomes an elementary tribosystem as a self-dependent energy transformer - it is capable not only of accumulating energy, but also of releasing it simultaneously! Synergy began working, namely simultaneous work of two opposing equalities - the accumulation of energy $\Delta U^*_D$ and its release $\Delta U^*_V$.

An unique state exists in stage 1-2. The system releases accumulated potential energy $\Delta U^*_D$ by the mechanism of simultaneous accumulation of potential energy $\Delta U^*_V$.

Point 2 - the point of equilibrium. This is the point of the superexcited state - the equilibrium state far from the state of the initial (zero) equilibrium. At point 2 (figure 9a) we have the equality of the densities of the accumulated potential energy of dislocation strengthening $\Delta U^*_D$ and of the accumulated potential energy of vacancies $\Delta U^*_V$ in the critical volume of friction $V_f^*$. This state of the critical volume of friction can be represented by the equivalent scheme shown in figure 9b. At point 2, the latent (potential) energy of the defects accumulates, equal to the double energy of the limiting deformation strengthening of point 1, i.e. $2 \cdot \Delta U^*_e = \Delta U^*_D + \Delta U^*_V$.

The state of point 2 is unique - characterized by a double energy balance. The coefficients of friction have a value of two (figure 6 and figure 7.) That’s why, on the experimental friction curves (figure 7b), we see that at point 2 the friction work $W_f$ is twice as high as the work of external forces $N_v$.

The principle of double energy balance of point 2 is a characteristic sign of self-organization!

Synergy of the area 2-3. Interaction of equal energy fields of dislocations $\Delta U^*_D$ and vacancies $\Delta U^*_V$ occurs in the critical volume of friction $V_f^*$ with the development of the process of returning accumulated potential energy due to the annihilation of defects in the crystal structure. There is a transformation of half the latent potential energy $\Delta U^*_D + \Delta U^*_V$ of point 2 into thermal energy $\Delta U^*_T$. We have an obvious synergy - the interaction of equal energy fields that determine a subsequent transformation.

Material Science aspect. Here, vacancies in the form of point defects (the smallest defects) of the crystal structure create the possibility for further development of the plastic deformation process. Dislocations begin to move due to the so-called mechanism of diffusion (vacancy) creep of dislocations. Vacancies are the most easily movable defects that accelerate all processes, in this case the process of plastic deformation. Dislocations go in passages (channels) – to the surface, grain boundaries, there are dislocations of opposite signs and the integrity of the crystal lattice is restored. A full return of accumulated potential energy is realized - the transformation of part of it into a related, heat component of internal energy $\Delta U^*_T$. There is an effect of self-heating of the critical volume of
friction $\Delta U_f^* = V_f^* \cdot \rho \cdot c_p \cdot dT_f$. This is the nature of the temperature flash $T_f$ in the body and in the contact of friction.

**Point 3 - the point of equilibrium.** The coefficient of friction at point 3 is again unity (see the figures 6 and 7b). This is equality of the accumulated internal potential energy $\Delta U_e^*$ of defects, and the internal thermal energy $\Delta U_T^*$ (the kinetic component of internal energy):

$\Delta U_e^* = \Delta U_{eD} + \Delta U_{eV} = \Delta U_T^* = Q$ (figure 10a). Such a state of the critical volume of friction $V_f^*$ can be represented by the equivalent scheme shown in figure 10b, where one half of the critical volume of friction $V_f^*$ has a reserve of potential energy of dislocations and vacancies $\Delta U_e^* = \Delta U_{eD} + \Delta U_{eV}$, and the second half possesses the energy of heat effect of friction $\Delta U_T^* = Q$.

![Figure 10. Schemes of the equilibrium state of the accumulated internal potential energy of dislocations and vacancies $\Delta U_e^* = \Delta U_{eD} + \Delta U_{eV}$ and the thermal (kinetic) component of internal energy $\Delta U_T^* = Q$ in the critical volume of friction $V_f^*$.](image)

As a result, a static energy oscillator (a self-dependent transformer) was formed; it is able to dissipate part of the internal energy - the kinetic energy component $\Delta U_T^*$ by a thermal conductance mechanism, in depth perpendicular to the friction surface. However, being a slow dissipation channel for the energy $Q$ - it takes time.

**Self-organization area 1-2-3.** The principle of point 2 with a double coefficient of friction and the principle of double energy balance generally characterize the synergy of self-organization. From the point of view of thermodynamics and tribology, there are, on the one hand, accumulation of potential energy $\Delta U_{eV}$ and change in the coefficient of friction from unity at point 1 to two at point 2, and on the other hand, release of the same part of the potential energy and its transformation into thermal energy $\Delta U_T^*$ with a decrease in the friction coefficient from two at point 2 to unity in point 3.

As a result, the evolution of the contact of friction, thanks to the self-organization, creates a state of point 3, which is more favorable than the states of point 1 and point 2. At point 3, the frictional contact (the elementary tribosystem) has a reserve of thermal energy $Q = \Delta U_T^*$ that can be released. The other part of the energy, the potential energy, can transform into a thermal one. As we see from the experiment (see figure 7), the frictional power and the work of external forces at point 3 are much higher (several times) than those in point 1.

**Synergy of the area 3-4.** The synergy in that case reflects the interaction (joint action) of two equal energy fields: of dislocations and vacancies $\Delta U_e^* = \Delta U_{eD} + \Delta U_{eV}$ (the potential component of internal energy) of the critical volume of friction $V_f^*$ and of thermal energy of the self-heating
\[ \Delta U^*_T = Q \] (the kinetic component of internal energy). The result of this interaction will be the formation of dissipative friction structures, which dissipate the accumulated energy of the balance components \( \tilde{Q} = V^*_f \cdot \tilde{q}^* \).

**Material Science aspect.** The temperature in the friction volume \( T_f \) of point 3 is equal to half the melting point \( 0.5 T^*_S \) of the most fusible material of the friction pair. This is a characteristic temperature, both for the recrystallization (the self-organization of a new, equiaxial structure in place of the extremely deformed one (distorted by defects)), and for the initiation of chemical reactions within the friction volume, which at the stage 2-3 communicated with the environment and realized an effect of self-doping. Defects came to the surface, and inside the bulk came substance of the environment, etc. The synergy of equal energy potentials of the activated surface (active centers) and the active substance of the environment was realized.

**Dissipative structures at friction.** As a result of the synergy effect, dissipative friction structures (third body [5] or secondary structures [9]) are formed in the region 3-4 (in figure 6). These dissipative friction structures possess the property of rapid dissipation of the energy \( \tilde{Q} \) of the thermal friction effect (see figures 6, 11). The main feature of these structures is that the structural dissipation principle is realized by them: the dissipation of accumulated energy is realized here; the energy is dissipated on the structural element (rather than inside it) in the form of elastic energy. Then the structural elements interact elastically and perform joint work (rotational modes of developed plastic deformation) of elastic visco-plastic flow (shift). The density of the energy of dynamic dissipative scattering \( \tilde{q} \) is equal to the critical accumulated density \( \Delta u^*_e \) of the potential energy. The system of the contact volume of friction \( V^*_f \) is under conditions of a flux of energy of critical density. In this case, the dissipation of energy by the dissipative structures takes place in the direction of motion, in contrast to the perpendicular direction of the energy scattering \( Q = \Delta U^*_T \). The scattered energy of dissipation \( \tilde{Q} \) is a fast analog of thermal conductivity. A detailed physical model of dissipative structures is considered below in the model of mechanical (nano) quantum.

**Figure 11.** Schemes of the state of the critical friction volume \( V^*_f \) in the area of compatibility (section 3-4 in figure 6).

**Point 4’ - the point of equilibrium** (with reference to figure 11). This point is located at the level of friction coefficient equal to 0.5 (figure 6,7). Here, the state of equilibrium is determined by the equality of the work of friction \( W_f \) and the power of the thermal effect of dissipative friction \( \tilde{Q} \). In sum, both these balance components are equal to the work of external forces \( Nv \) (figure 7b.) The neighborhoods of this point in the region 3-4 (figure 6, 7b) can have a wide range of the structural
arrangement of the critical volume of friction $V_f^*$, in which the fraction of the dissipative volume of friction $V_{dis}$ will vary (figure 6) from the minimum (point 3) to the maximum (point 4). Accordingly, the proportion of the adaptive volume of friction $V_{adapt}$ will vary inversely with the change of $V_{dis}$.

**Point 4 - the point of ideal equilibrium** (with reference to figure 6 and figure 11). The states and properties of this point are presented below in the idea of the mechanical (nano) quantum, as an attractor of the limit cycle for the process of plastic deformation at friction. This is the case of maximum realization of synergy as joint cooperative action.

7. The idea of mechanical (nano) quantum

Result of the ideal evolution of the elementary tribosystem is the formation of a unique nanostructure - a mechanical (nano) quantum. Strict concept about the mechanical quantum has been obtained [2, 10] considering the equation of a quasi-ideal solid body in point 4 of the friction evolution diagram, as follows:

$$\dot{Q}^* = \tilde{S}_Q T = \mu_{dis}^* Nl_f = U_f^* = V^*_f = V_{dis}^* = const,$$

which is a particular case of equation (8) solution of the energy balance of friction, with $\mu_{adapt} = 0$ and $\mu_{dis} = 1 = \mu_{dis}^*$. Here $\tilde{S}_Q$ is the inertial entropy of the compatible friction volume; $T$ - characteristic temperature of the friction contact volume; $l_f$ - linear size of the friction volume.

Accordingly, under conditions of maximum compatibility (point 4), when the tribosystem realizes a complete evolutionary cycle of adaptation with formation of a perfect dissipative structure, its structure behaviour obeys the equation of quasi-ideal solid body state, i.e. it should be assumed that the interactions between the structure elements are minimized, namely as for the state of ideal elasticity in dynamics.

Taking into account the Planck-Boltzmann formula $S = k \ln W$ and the real number of atomic oscillators $N_f$ in the volume of an elementary tribosystem $V_f^*$, equation (13) is reduced to the form:

$$\mu_{dis} = \frac{\tilde{S}_Q T}{Nl_f} = \frac{kTN_f \ln W}{Nl_f};$$

$$\mu_{adapt} = 1 - \mu_{dis} = 1 - \frac{kTN_f \ln W}{Nl_f} = 1 - \frac{\tilde{S}_Q T}{Nl_f} = S_U T,$$

explaining the friction laws from the point of view of the evolution of systems. The tribosystem always tends to some optimal state characterized by $\mu_{adapt}$, i.e. to the most probable state $W' = N_f \ln W$ for these friction conditions. Here $N_f$ is the number of atoms (oscillators) in the friction volume $V_{max} = V_f^*$; $k$ - Boltzmann's constant; $W$ - state probability; $S_U$ - configurational entropy of the compatible friction volume.

Analysis and solution of these equations [2] allow us to show the probability value $W$ constancy (the parameter of state (order) of the tribosystem) for the entire range of compatible friction, namely $\ln W = 3$ and $W = e^3 = 20,085,53696$.

The value of thermodynamic probability $W$ of the state equal to $20,085,53696$ was interpreted [2] as the minimum number of linear, atomic oscillators in one of the three directions of the minimum adaptive friction volume $V_{min}^*$, corresponding to the state of absolute elastic friction - abnormal low
friction (the safe threshold of deformation). Accordingly, the number of atomic oscillators in this volume is $W^3 = 8103,083969...$

On the other hand, taking the entropy $S$ as Boltzmann entropy, a universal friction constant $R_f = kN_f$ [2] is obtained, which in physical sense characterizes the "energy dimension" of an elementary tribosystem ($TS$), containing under ideal conditions the same number of atomic oscillators $N_f$ (mechanical quanta $N_Q$).

$$R_f = k \cdot N_f = k \cdot W^3 \cdot N_Q = R_{MQ} \cdot N_Q \left( \frac{J}{\text{grad} \cdot TS} \right); \quad (16)$$

$$R_{MQ} = k \cdot W^3 \left( \frac{J}{\text{grad} \cdot TS} \right). \quad (17)$$

As follows from the calculations [2, 10], the size of the minimum adaptive friction volume $V_{adapt}^{min}$ coincides in magnitude with the size of the submicroscopic zone at the crack mouth, which is $(4/9) \cdot 10^{-9} mm$ for metals, i.e. with the size of the critical volume responsible for the destruction. Thus, the size of the minimum adaptive friction volume $V_{adapt}^{min} = V_{class}$ can be presented as the size of a certain mechanical "Quantum". This mechanical quantum consists of the minimum number of atoms which are capable to provide such a configuration (structure) that has the property of reversibly receive and dissipate (return) the energy of the external mechanical motion (action). It also represents the smallest structural formation under conditions of plastic deformation and is formed during the transition of the tribosystem (the deformable volume) through the extremely activated (critical) state (figure 2), due to the development of self-organizing processes of tribosystem adaptation. Calculations show that in the volume of friction $V_f^*$ the number of such mechanical quanta is equal to the number $0,63 \cdot 10^4$ [2], i.e. to the safe number of fatigue cycles.

The mechanical quantum itself is a dynamic oscillator of dissipative friction structures and its linear size is equal to the radius of a spherical ideal crystal:

$$D_Q = 2R_{MQ} = \sqrt{\frac{3 \cdot W^3}{4 \cdot \pi}} a \approx 7,177 \ nm. \quad (18)$$

Here $a$ is the average atom diameter.

The mechanical quantum should be regarded as an elementary nanostructure of a metallic solid. Figure 12 shows a constructed model of this atomically-rough theoretical crystal [2, 10-12], consisting of 8103 cubic atomic cells.

**Figure 12.** Ideal crystal model of the elementary nanostructure of friction contact [10-12]

The mutual rotational-vibrational motion of these mechanical quanta relative to each other inside the elementary tribosystem determines the state of the perfect dissipative structure of friction. Actually, such a state is described by the equation of state of a quasi-ideal solid body (13), a state where the interaction between the structure elements (the mechanical quanta) is minimized - the state of ideal
elasticity of the quasi-viscous flow. The calculated friction coefficient between quanta is about $10^{-8}$ [2, 10-12].

8. Synergy of tribosystem’s compatibility and optimality of state

The ideal, quasi-elastic state of friction contact at its complete evolution consists in the effect of the complete dissipation of external mechanical motion energy on the newly formed (by the mechanism of self-organization in the vicinity of the critical state) structural elements - mechanical quanta (dynamic oscillators). These oscillators realize their most complete rotation-vibrational behavior relative to each other in the volume of the elementary tribosystem. The resistance to their relative interaction is minimal, it is elastic and corresponds to the elasticity of ideal atomic (in thermodynamic equilibrium) interactions.

The universal constants of a mechanical quantum and an elementary tribosystem (a material point) are defined as quantum model of surface damping

$$
\mu_{\text{dis}} = \frac{3R_{aq}T n_i}{N I_f} = \frac{U_{ij}n_i}{U_{ij}n_s} = \frac{n_i}{n_s} = 1 - \mu_{\text{adapt}}; \quad \mu = 1 - \frac{n_i}{n_s} = \frac{n_{\text{dest}}}{n_s},
$$

(19)

taking into account the destruction quanta $n_{\text{dest}}$ (irreversible component of the process) and the damping quanta $n_i$ (reversible, elastic component (number of fatigue)), as well as the probabilistic model of the evolution of the tribosystem towards the most ordered state

$$
\mu_{\text{adapt}} = 1 - \mu_{\text{dis}} = 1 - \frac{R_f T \ln W_i}{N I_f} = 1 - \frac{\ln W_i}{\ln W_*}.
$$

(20)

Here $R_{aq}$ is the constant of deformation (friction); $3R_{aq}T = U_{ij}$ - the energy of one mechanical quantum; $W_i$ and $W_*$ - current and limiting probabilities of states for the compatible tribosystems.

According to the model of quantum damping of surfaces at friction, under the conditions of complete evolution (adaptation) of the elementary tribosystem, all mechanical quanta except one transform elastically and reversibly the energy of external action (the mechanical motion). One mechanical quantum of radiation ($\approx 8103$ atoms) is a minimal loss (the essence of wearlessness or the standard of wear).

Actually, the principle of the mechanical quantum determines the nano quantum levels of all friction parameters of compatible friction surfaces [10-12], etc.

In such a way, one can speak of synergism in the evolution of friction, which manifests itself in the emergence of really new properties in the wholeness - the elementary tribosystem formed in point 2 - the center of self-organizing processes. These new properties are the essence of the collective, joint interaction of the assembly of mechanical (nano) quanta in point 4 of the ideal evolution of the tribosystem. The nanoquanta as tribo-subsystems in their elastic interaction realize the highest compatibility of tribomaterials and, accordingly, the maximum life of the elementary tribosystem.

The mechanical quantum, therefore, can be regarded as the smallest substance amount of a solid body, which has the sign of the latter. This quantum is really mechanical, because the next independent structural and material formation will be the atom. Thus, the mechanical quantum is precisely an asymptotically stable attractor of the limit cycle type for a deformable solid body (at friction). It really represents a limit in the structural evolution of a solid body and characterizes the ultimate durability of the working cycle of a rubbing pair.
9. Conclusions

1. Friction is a global process of joint action (work) of two surfaces in contact.
2. The synergy (joint action) of two rubbing surfaces activates the generalized mechanisms of transformation and dissipation of their external relative motion energy, which strictly obey the principle of energy balance.
3. The energy balance of friction characterizes in summarized form the adaptive, dual nature of a friction process - the competition of two simultaneously acting, interrelated and opposite tendencies: accumulation of internal energy by the deformable contact volume and its release.
4. The balance process of friction determines the essence of synergy principle - the equality of the joint action of two interrelated and opposite tendencies: accumulation of internal energy and its release.
5. Equality of the combined effect of the two opposite energy tendencies of the friction process activates the mechanisms of self-organization of the friction system (the deformable contact) as an evolution system.
6. In consequence of self-organization of the tribosystem (the contact volume), the latter evolves formation within itself of tribo-subsystems - structural units of an essentially new (unique) level. Thus, dissipative structures of friction are formed.
7. The basis of friction dissipative structures is a mechanical (nano) quantum - the smallest structural formation under conditions of plastic deformation, which has the property of maximal reversible receipt and return (dissipation) of the energy of external mechanical motion (action).
8. As a dynamic oscillator of friction dissipative structures the mechanical (nano) quantum is an attractor of the limit cycle for the process of plastic deformation (of friction). There is a maximum realization of synergy - a joint action of tribo-subsystems with minimal elastic interaction.
9. A maximum load capacity of the tribosystem is completed - the external load is received elastically at the internal level of the elementary tribosystem (contact). The tribosystem realizes abnormal low friction and minimal contact loss in the form of a single mechanical quantum (standard of wear) for the act of the contact loading. The highest fatigue strength and durability occur: "wearlessness" with the effect of a natural solid lubricant (the “servovite” film).

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