Structural-energetic regularities of tribocontact evolution

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Structural-energetic regularities of tribocontact evolution*

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Abstract. The contact of friction lives with its own very interesting life. It gets evolved. This evolution of contact changes the states and properties of it. How can we describe the tribocontact evolution? Any nature systems are very well described by thermodynamic method. The contact of friction has the system properties and therefore one may use thermodynamic approach. From thermodynamic point of view friction is a competition of two simultaneous, interconnected and opposite tendencies of accumulating latent (potential) energy of various kinds of defects and damages of contact volumes structures and releasing (dissipation) energy due to various relaxation processes. This friction adaptive-dissipative model for analysis of evolution of tribocontact as elementary tribosystem is examined.

1. Introduction
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].

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 of 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] is based on the analysis method to plastic deformation of ergodynamics of deformed solids [2-4]. Ergodynamics is a synthesis to the problem of deformation most general laws of thermodynamics for non-reversible 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 (energetical) 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 $\Delta U_e$ of various kinds of defects and damages of contact volumes structures and releasing (dissipation) energy $Q$ due to various relaxation.

The major distinction of triboergodynamics from general ergodynamics of deformed solids is «scale factor» which exhibits itself in existence of critical friction volume. This volume determines the

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limit friction parameters and separate, in essence, the surface deformation from the traditional volume deformation.

2. Structural-energetic interpretation of friction process

As it is known friction is characterized as a product of frictional forces $F$ by friction distance $\ell$, that is, the work $\omega_f$, expended on overcoming frictional forces

$$\omega_f = F\ell,$$  \hspace{1cm} (1)

According to the energy balance scheme (figure 1) for plastic deformation and fracture [4] presented below, equations for elementary friction work $\omega_f$ (without lubrication) has the view:

$$\omega_f = \Delta u_e + q,$$  \hspace{1cm} (2)

$$\dot{\omega}_f = \dot{u}_e + \dot{q}.$$  \hspace{1cm} (3)

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

![Figure 1. Scheme of the energy balance for the plastic deformation of a solid body [1-4].](image)

Since the contact volumes of both materials of the friction pair (figure 2) are deformed, Equations (2) and (3) should be rewritten as:

$$\omega_f = \Delta u_{e1} + \Delta u_{e2} + q_1 + q_2,$$  \hspace{1cm} (4)

$$\dot{\omega}_f = \dot{u}_{e1} + \dot{u}_{e2} + \dot{q}_1 + \dot{q}_2.$$  \hspace{1cm} (5)

These equations show, that from thermodynamic point of view, the work $\omega_f$ of friction forces, (friction power $\dot{\omega}_f$) may be divided conventionally into two specific parts.

The first part is related to variation of the latent (potential) energy ($\Delta u_{e1}$ and $\Delta u_{e2}$) in deformed (contact) volumes. This is the energy of various simple defects and damages which are generated and accumulated in the bulk. This energy is unique and the total characteristic of submicro-and
microstructural variations occurring in plastically deformed volumes [2-4]. This is a measure of strain hardening and damage of material.

![Figure 2. Schematic view of friction’s contact](image)

The second part of the friction work \( \omega_f \) is related to dynamic recovery which is accompanied by releasing latent energy and thermal effect of friction \( (q_1, q_2) \). This energy involves displacement and annihilation of various simple defects of opposite sign terminating at the free surface, healing reversible submicroscopic discontinuities, etc.

The relations between \( \Delta u_{e1} \) and \( \Delta u_{e2} \), as well as \( q_1 \) and \( q_2 \) are defined by physico-chemical properties of the materials of the friction pair, their structure and friction conditions.

Since the contact volumes (not unit sizes) of the materials forming a friction couple become strained by friction (figure 2), equations (4) and (5) can be rewritten in the form:

\[
W_f = \Delta U_e + Q = \Delta U_{e1} + \Delta U_{e2} + Q_1 + Q_2, \tag{6}
\]

\[
W_f = \dot{U}_e + Q = \dot{U}_{e1} + \dot{U}_{e2} + Q_1 + Q_2. \tag{7}
\]

Consequently, the equations for friction work \( W_f \), frictional force \( F \) and friction coefficient \( \mu \) (without lubrication) has the view:

\[
W_f = \Delta U_e + Q = \Delta U_{e1} + \Delta U_{e2} + \Delta U_{T1} + \Delta U_{T2} + \dot{Q}_1 + \dot{Q}_2. \tag{8}
\]

\[
W_f = \dot{U}_e + Q = \dot{U}_{e1} + \dot{U}_{e2} + \dot{U}_{T1} + \dot{U}_{T2} + \dot{Q}_1 + \dot{Q}_2. \tag{9}
\]

\[
F_l = \frac{\Delta U_{e1} + \Delta U_{e2} + \dot{Q}_1 + \dot{Q}_2}{l} = F_{\text{mechanical}} + F_{\text{molecular}}, \tag{10}
\]

\[
F_v = \frac{\dot{U}_{e1} + \dot{U}_{e2} + \dot{Q}_1 + \dot{Q}_2}{v} = F_{\text{mechanical}} + F_{\text{molecular}}, \tag{11}
\]

\[
\mu_l = \frac{\Delta U_{e1} + \Delta U_{e2} + \dot{Q}_1 + \dot{Q}_2}{Nl} = \mu_{\text{adapt}} + \mu_{\text{dis}} = \mu_{\text{adapt}} + \mu_{F(\text{dis})} + \mu_{\dot{Q}(\text{dis})}, \tag{12}
\]

\[
\mu_v = \frac{\dot{U}_{e1} + \dot{U}_{e2} + \dot{Q}_1 + \dot{Q}_2}{Nv} = \mu_{\text{deformation}} + \mu_{\text{adhesion}}. \tag{13}
\]

where \( \Delta U_e = V_f \Delta u_e \); \( Q = V_f \dot{q} \); \( \dot{Q} = V_f \ddot{q} \); \( \dot{U}_e = V_f \dot{u}_e \); \( \dot{u}_e = \frac{d u_e}{d t} \) - is the rate of latent energy density change in the contact volumes; \( V_f \) - is the deformable (friction) volume; \( \mu \) - friction coefficient; \( \mu_{\text{adapt}} \) - adaptive friction coefficient; \( \mu_{F(\text{dis})} \) and \( \mu_{\dot{Q}(\text{dis})} \) - statical and dynamical components of dissipative friction coefficient; \( \Delta U_T \) - thermal component of internal energy; \( \Delta U_{T1} \) - thermal component of internal energy; \( N \) - normal load; \( l \) - distance of friction; \( v \) - sliding velocity. The latent energy density \( \Delta u_e \) is an integral parameter of tribostate and damageability (failure \( \Delta u_e^* \)).
Thus, viewed thermodynamically, the work done by friction forces \( W_f \) (the friction power \( \dot{W}_f \) ), the friction force \( F \) and the friction coefficient \( \mu \) may be classified conventionally into two specific components with different kinetic behavior [3]. 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. This energy is a unique and integral characteristic of the submicro- and microstructural transformations that occur in plastically strained materials [2]. 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 \( \Delta u_{e1} \) and \( \Delta u_{e2} \) 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 for the force \( F \) and coefficient of friction \( \mu \), which agrees with current concepts [5,6] of the nature of friction – molecular-mechanical theory (11) and deformable-adhesion theory (13). But it is more correct to speak about the adaptive-dissipative nature (model) of friction (12).

Relationships (6)-(13) which generalize the mechanism of energy dissipation at friction allow to classify the tribosystem states. According to ergodynamics of deformed solids (relationships \( \Delta u = \Delta u_e + \Delta u_T \) and \( q = \Delta u_T + \dot{q} \)) and equations (6)-(7) may be transformed to:

\[
W_f = \Delta U_{e1} + \Delta U_{e2} + \Delta U_{T1} + \Delta U_{T2} + \dot{Q}_1 + \dot{Q}_2,
\]

\[
\dot{W}_f = \dot{U}_{e1} + \dot{U}_{e2} + \dot{U}_{T1} + \dot{U}_{T2} + \dot{\dot{Q}}_1 + \dot{\dot{Q}}_2.
\]

As follows from equations of energy balance (14), (15), 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 (14), (15), which are responsible for accumulation of internal energy in deformed volumes \( \Delta u = \Delta u_{e1} + \Delta u_{e2} + \Delta u_{T1} + \Delta u_{T2} \), 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 \( \dot{q} = \dot{\dot{q}}_1 + \dot{\dot{q}}_2 \) of friction contact.

In its turn, the first state may be classified depending on the relation between potential \( \Delta u_e \) and kinetic \( \Delta u_T \) 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 \( \Delta u_T \) 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 component \( \Delta u_e (\Delta u = \Delta u_e) \). 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 (6) should be written as:

\[
W_f = \Delta U_{e1} + \Delta U_{e2} + \Delta U_{e3} + Q_1 + Q_2 + Q_3.
\]

In the special case, where the friction is localized into volume of the "third body" (figure 2) equation (16) develops into
\[ W_f = \Delta U_{e3} + \dot{Q}_3. \]  

Here \( \Delta U_{e3} = V_f \Delta u_{e3} \).

3. Energy interpretation of Leonardo da Vinci (Amonton’s) friction coefficient

According to thermodynamic theory of strength [2], 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 density \( \Delta u_e \)) 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 (12)-(13) that the Amonton (Leonardo da Vinci) friction coefficient is:

\[ \mu = \frac{\Delta U_e}{\mu^* N l} = \frac{F}{N}; \quad F = \frac{\Delta U_e}{l}; \quad Q = 0, \quad \mu^* = 1. \]  

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 \( \Delta U_e \), 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 \( e_\Delta U \) 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 \( \Delta U_e = \Delta u_e \) is defined by 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 regularities of rubbing surfaces evolution

We propose an energetic interpretation of the experimental friction curves \( \mu = \mu(N,v) \) [5,7] in view of structural-energy diagram (figure 3) for evolution of rubbing surfaces. According to our concept [1], the ascending portion of the friction coefficient curve \( \mu \) is mainly controlled by processes associated with the accumulation of latent energy \( \Delta U_e \) in various structural defects and damages. Here the increase in \( \mu \) is due to the increasing density of latent (potential) energy \( \Delta u_e \) and the increasing adaptive friction volume \( n_a \). The descending portion of the friction curve is mainly controlled by processes associated with the release and dissipation of energy \( Q = \Delta U_f + \dot{Q} \). Here the decrease in \( \mu \) 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 \( V_{dis} (\dot{q}^* = u_e^*) \).

Evolution of tribosystem, presented as a diagram view (figure 3), has an adaptive-dissipative character (6)-(13) and reflects the competitive (dialectical) nature of friction. Evolution curve has the row of principal points (1-5) of transitional tribosystem states, which strictly obeys the balance principle of friction; there are more characteristic areas of tribosystem behavior between these points. These areas reflect the common properties of nonlinear dynamic of evolution. So, in figure 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.

Figure 3. Structural-energy diagram for evolution of rubbing surfaces [1].

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 (figure 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 \( \Delta u_e \) to a limited magnitude \( \Delta u_e^* \) 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 (figure 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 (figure 4). 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 \( \Delta u_e \) 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.
Figure 4. A schematic evolution of the contact volume of friction in diagram’s points 1-5 [1].

Suggested theoretical and calculation estimation [1] showed that dissipative friction volume performs reversible elastic energy transformation of outer mechanical movement with density $\dot{q}^*$ equal to critical density of latent energy $\rho^*$. Culmination of tribosystem evolution is its final and limited condition of point 4 – a state of anomalously low friction and wearlessness (maximum efficient).

A schematic evolution of the contact volume of friction in diagram’s points 1-5 is presented in figure 4.

The calculation [1] shows that at an ideal tribosystem evolution an adaptive (Amontons) friction coefficient $\mu_{\text{adapt}}$ in a point 2 of a diagram falls abruptly down, reaching in a point 4 the value of elastic friction coefficient $\mu_{\text{elast}}$. For point 4 of compatibility area 3-4 an equation of energy balance (12) should be put in the following way:

$$
\mu_{\text{adapt}} = \mu^* - \mu_{\text{dis}} = 1 - \mu_{\text{dis}} = \mu_{\text{plast}} = 0 = \mu_{\text{elast}} ; \quad \mu^* = 1.0 .
$$

Thus, point 4 stands for an ideal evolution of contact friction volume a condition of ideal elastic-viscous-plastic deformation. Equation (19) shows as a matter of fact exactly it, i.e. Amontons friction coefficient $\mu_{\text{adapt}}$ being in its essence plastic friction coefficient $\mu_{\text{plast}}$ has a minimum value equal to zero. It follows then, that plastic friction became elastic with friction coefficient $\mu_{\text{elast}}$. It means that plastic deformation of contact volume friction is implemented with the maximum dynamic dissipation ($\dot{Q} = \text{max}$) 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 full evolution of contact volume. From the physics point of view this condition may be explained by the full dissipation of accumulated energy $\Delta U_e^*$ in point 2 and by newly emerged structures of point 4 in the form of elastic energy of interaction between them (dynamic dissipation energy $\dot{Q}^*$). Here $\mu_{\text{dis}} = 1.0$. The structural elements themselves are defectless - $\mu_{\text{adapt}} = 0$, and friction is elastic - $\mu = \mu_{\text{elast}}$.

It has been demonstrated [1] that value of minimum adaptive friction volume $V_{\text{adapt}}^{\text{min}}$ corresponding to the zero meaning of plastic friction component $\mu_{\text{adapt}}$ is not equal to zero, but is equal to some minimum structural element of deformed solid body.
5. Mechanical or nano quantum idea

As the result of more complete evolution of elementary tribosystem (figure 3, point 4) the unique nanostructure is formed and the basis of which is one mechanical (nano) quantum [8]. This mechanical quantum represents the minimum number of atoms that can be arranged in a structure capable of reversibly absorbing and dissipating (recovering) the energy of external mechanical motion. Mechanical quantum represents the least structural form of solid material body in conditions of plastic deformation too and under transition tribosystem across the limit activated state by development of selforganazing processes of tribosystem adaptation are formed. The universal size (volume) of mechanical quantum (2) is equal to:

\[ V_Q = (e^3)^3 = (20,08553695)^3 = 8103,083969 \text{ atom’s oscillators}. \]  \tag{20}

Mechanical quantum is dynamic oscillator of dissipative friction structure. Linear size of it quantum (3) is equal to diameter of spherical ideal crystal:

\[ D_Q = 2 \cdot W \cdot d_a \cdot (3/4 \cdot \pi)^{1/3} = 7,177nm. \]  \tag{21}

Here \( d_a \) - mean atomic diameter for metals; \( W = e^3 \) - parameter of state for mechanical quantum.

Mechanical quantum (figure 5) can be examined as the elementary nanostructure of metal’s solid body. Calculations have shown the number \( N_Q \) of such mechanical «quanta» (subtribosystems) within the elementary tribosystem’s volume \( V_f^* = V_{dis}^* \) to be \( 0,63 \cdot 10^6 \), which is close to the safe number of fatigue cycles.

\[ \]

**Figure 5.** Model of elementary nanostructure of friction (8103 atomic cubical cells) [1,8].

In these terms (point 4) only one mechanical quantum is the lost – standard of wear. The tribosystem (friction contact) has the ideal damping properties – «wearless».

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

6. Conclusions

1. From the energy balance equations of friction follows that the evolution of tribosystem has an adaptive-dissipative character.
2. Friction is a competition of two simultaneous, interconnected and opposite tendencies of accumulating latent (potential) energy of various kinds of defects and damages of contact volumes structures and releasing (dissipation) energy due to various relaxation.
3. The most complete evolution of tribosystem has symmetrical view - the friction process is started and finished within elastic area.
4. The unique nanostructure at the basis of which is one mechanical (nano) quantum is formed by elastic-ductile-plastic and dynamic dissipative state of ideal tribocontact.
5. We can suggest the mechanical quantum as the least structural form of solid material body (subtribosystem) and the standard of wear.
6. All parameters of compatibility (optimal) friction have to be in quanta levels - commensurable with the parameters of the one mechanical quantum.

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