

Energy Balance of Friction and Friction Coefficient in Energetical Interpretation

S.V. Fedorov^a

^aDepartment of Theory of Mechanisms and Machines and Machine Elements, Kaliningrad State Technical University, Russia.

Keywords:

Friction
Energy
Balance
Deformation
Structure
Tribosystem evolution

ABSTRACT

Sliding friction energy model is proposed. In this model, generalized mechanism of transformation and dissipation of energy under friction the model of elastic-plastic deformation and fracture contact volumes is considered. Energy model of the process of plastic deformation and destruction of solid bodies is based on the concept of ergodynamic of deformable bodies. Equations of energy balance of friction within the structural and energetic interpretation of deformation are proposed. The energy interpretation of the coefficient of friction is showed. From this position the friction coefficient is the most informative characteristic of the process. Experimental friction curves have been generalized. As a result of the energy analysis of friction, the energy diagram of the structural evolution of the friction surfaces is suggested.

© 2015 Published by Faculty of Engineering

Corresponding author:

Sergey Vasily Fedorov
Kaliningrad State Technical University,
Department of Theory of Mechanisms
and Machines and Machine Elements,
Russia.
E-mail: fedorov@kgtu.ru

1. INTRODUCTION

When you create a generalized engineering theory of friction, the friction model has an important place. This model should disclose the mechanisms of friction and adequate physical nature of this phenomenon.

A suggestion is to use a generalized model of friction, the model of elastic-plastic deformation of the body element, which is located on the surface of the friction pairs. This model is based on our new engineering approach to the problem of friction-triboergodynamics.

Triboergodynamics [1] is an extension (one of its parts) of general ergodynamics of deformable bodies [2-6]. 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.

Triboergodynamics is based on modern knowledge of friction, too:

- 1) Friction is a phenomenon of resistance to relative motion between two bodies, originating at their surfaces contact area;

- 2) Friction is the process of transformation and dissipation of energy of external movement into other kinds of energy;
- 3) Friction is the process of elastic-plastic deformation localized in thin surface layers of rubbing materials.

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

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

2. SHORT FUNDAMENTALS OF ERGODYNAMICS

2.1 Structural model

Deformable body is considered as an open, multicomponent, substantially non-homogeneous and nonequilibrium system with hierarchy of different levels (from submicro- to macrolevel) of metastable structural elements (defects and damages) which are statistically uniformly distributed in the volume. Some of these elements are virtual sources and sinks of elementary defects (vacancies, dislocations, etc.), while the others are a barrier to their motion.

The structure state is defined by the basic parameters [6]: γ_σ is the overstress factor of interatomic bonds which evaluates nonuniformity of external stresses σ distribution in the bonds σ^0 ($\gamma_\sigma = \sigma^0 / \sigma \geq 1$); u_e is the density of latent (free) energy of defects and damages; ν is the coefficient of nonuniformity of latent energy distribution in volume, which is equal to ratio between latent energy density in local volume u_e^0 and average value of u_e ($\nu = u_e^0 / u_e$). A complex structural parameter $k = \gamma_\sigma / \nu^{0.5} = \sigma_* / S_*$ specifies a relationship between theoretical σ_* and actual S_* strength of a solid body.

2.2 Physical model and structural-energetic interpretation of the process

Macroscopic phenomenon – plastic deformation and fracture of the body element is considered as a cooperation of a huge number of microscopic elementary acts of atomic-molecular regroupings under external force field (mechanical, thermal, electrical, etc.) which are activated by the thermal energy fluctuations. From the thermodynamic point of view, all the mechanisms and structural levels of the process are divided into two most characteristic groups of adaptive and dissipative (relaxation) types. They differ in physical nature and kinetic behavior. The simple acts controlling generation and accumulation of unit defects in deformed body element (damage) are classified as the first group. The specific (referred to unit volume) pumping power of excessive (latent) energy \dot{u}_e is an overall characteristic of the processes rate:

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

The mechanisms and simple acts controlling relaxation (dissipative) processes of plastic deformation are classified as the second group. The specific power of thermal effect \dot{q} of plastic deformation is overall characteristic of the processes:

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

Here A and B are the kinetic coefficient:

$$A = \frac{2kT}{hV_0} \sum_1^n U'_i(\sigma_0, T) \exp \left[-\frac{U'(\sigma_0, T)_i}{kT} \right], \quad (3)$$

$$B = \frac{2kT}{hV_0} \sum_1^n U''_i(\sigma_0, T) \exp \left[-\frac{U''(\sigma_0, T)_i}{kT} \right], \quad (4)$$

$$\begin{aligned} U'_i(\sigma_0, T) &= U'_{0i} + \Delta U'(T) \pm \beta \sigma_0^2, \\ U''_i(\sigma_0, T) &= U''_{0i} + \Delta U''(T) \pm \beta \sigma_0^2, \end{aligned} \quad (5)$$

$$\alpha = \frac{\gamma_\sigma^2 V_0}{6G}, \quad \beta = \frac{\gamma_\sigma^2 V_0}{2K}. \quad (6)$$

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

2.3 Thermodynamic analysis of interrelation between deformation and fracture

From the thermodynamic point of view, the plastic deformation and the fracture are defined by a competition of two opposite interrelated and simultaneous trends: growth of latent energy density u_e of various defects and damages which are generated and accumulated in the material due to work done by the external forces ω_p and reduction (release) of the density as a result of relaxation processes in deformed body element. The first trend is concerned with strain hardening and damage of material, the second – with dynamic recovery and dissipation of the strain energy which govern the thermal effect of plastic deformation q .

A significant portion of the dissipative energy q is not retained in the deformed element, but passes through it and is dissipated in the environment due to heat exchange \bar{q} . Only the insignificant portion of the energy q is accumulated in deformed element as a heat component of internal energy $\Delta u_T = q - \bar{q}$ increasing its temperature (self-heating effect).

According to conservation law:

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

In mechanics of deformable solids the irreversible work ω_p and power of deformation $\dot{\omega}_p$ are related to stress-strain state of the element by:

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

From (7) and (8) a one-to-one relation follows between stress-strain and thermodynamic states of the element:

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

Consequently, from thermodynamic point of view, the total values of work ω_p and irreversible strain ε_i^p as well as their rates $(\dot{\omega}_p, \dot{\varepsilon}_i^p)$ may be presented as a sum of two components related to strain hardening and damage $(\varepsilon_i^p = \dot{u}_e / \sigma_i)$, and dynamic recovery $(\dot{\varepsilon}_i^q = \dot{q} / \sigma_i)$ controlling quasi-viscous flow of the body element, respectively.

This deduction is of important value in analyzing interrelation between deformation and fracture processes. Only a portion of plastic (irreversible) strain ε_i^e , which is controlled by microscopic processes related to strain hardening and accumulation of latent energy of defects and damages, is responsible for damage and fracture of the body element. The significant portion of the irreversible strain ε_i^q controlled by relaxation (dissipative) processes does not effect the damage and fracture of the body element and only causes quasi-viscous flow (steady state creep). The relationship between work and extent of irreversible deformation and their components varies in a very wide range and depends on the structure and deformation conditions of the material [2].

2.4 Thermodynamic condition of local fracture

As a parameter of damage (scattered fracture), the density of internal energy stored in the deformed volume, will be taken. The energy is defined as a sum of two components: potential (latent) energy u_e and kinetic (thermal) energy u_T that is:

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

The energy is related to static (Δu_e) and dynamic (Δu_T) damages and distortions of crystal lattice in deformed body. Consequently, it is responsible for scattered fracture (damage).

The body element is looked upon as fractured, if at least in one local volume responsible for fracture the internal energy density reaches the critical (ultimate) value u_* . This value corresponds to the loss of stability "in great" by crystal lattice. At this instant, the cracks of critical size (after Griffith-Orowan-Irwin) and sharp localization of the process at the crack tip occur in a local volume. The thermodynamic condition of local fracture is written as:

$$u(\bar{r}_*, t_*) = u(\bar{r}_*, 0) + \int_0^{t_*} \dot{u}(\bar{r}_*, t_*) dt = u_* = \text{const}, \quad (11)$$

where: $u(\bar{r}_*, 0)$ is density of internal energy of the material in initial (before deformation, $t = 0$) state; $u(\bar{r}_*, t)$ is specific power of internal energy sources in local macro volume of the material

responsible for fracture; \bar{r}_* is parameter characterizing coordinates (x_*, y_*, z_*) of the local volume responsible for fracture.

2.5 Thermodynamic criterion of fracture

According to the structural-energetic analogy between mechanical fracture and melting of metals and alloys [7] and experimental data [2], the critical value of internal energy u_* in the local volume responsible for fracture agrees with known thermodynamic characteristic of material ΔH_s (enthalpy of melting):

$$u_* = \Delta H_s = \int_0^{T_s} c_p dT + L_s, \quad (12)$$

where: T_s is melting temperature; c_p is specific heat; L_s is latent melting heat.

2.6 Relationship between force and energy criteria of local fracture

The analysis of kinetic equation of state (damage) (1) indicates that the real solid body approaches the stationary (stable) state under constant action of external fields ($\sigma_0 = \text{const}$, $\sigma_i = \text{const}$, $T = \text{const}$) if:

$$\Delta u_e = \text{const} \text{ and } \dot{u}_e = 0. \quad (13)$$

From the kinetic equation (1) under condition (13) an important consequence follows:

$$\sigma_i = \sigma_s, \sigma_s = \left(\frac{\nu u_e}{\alpha} \right)^{1/2} = \frac{1}{k_\sigma} (6G u_e)^{1/2}, \quad (14)$$

according to which the structure state of material $\sigma_s(\alpha, u_e, \nu)$ adapts (shakes down) in a stable stage to external conditions, which are defined unambiguously by deviatory component of the stress tensor σ_i ($\sigma_s = \sigma_i$). Relationship (14) generalizes the known proposition of dislocation theory on mutual relation between the flow stress σ_s and the density of latent (stored) energy u_e [8] for the case of combined stress state. The material damage u_e in the local volume, responsible for fracture becomes critical; therefore, relationship (14) makes it possible to estimate the actual strength of the material S.

$$S = \left(\frac{\nu u_e}{\alpha} \right)^{1/2} = \frac{1}{k_\sigma} (6G u_e)^{1/2}. \quad (15)$$

Here:

$$u_e = u_e - u_{T_0} = \Delta H_s - \int_0^{T_s} c_p dT. \quad (16)$$

From (15) and (16) under $k_\sigma = 1.0$ and $T = 0$ the theoretical shear strength is:

$$\sigma_* = (6G \Delta H_s)^{1/2} = \left(\frac{3E \Delta H_s}{1 + \mu} \right)^{1/2}, \quad (17)$$

where: E and μ are elasticity modulus and Poisson's ratio.

3. TRIBOERGODYNAMICS – ERGODYNAMIC ANALYSIS OF FRICTION

Friction is known to be a product of frictional forces F by friction distance l , that is, the work ω_f for unit volume, expended on overcoming frictional forces:

$$\omega_f = Fl, \quad (18)$$

$$\omega_f = \Delta u_e + q, \quad (19)$$

or

$$\dot{\omega}_f = \dot{u}_e + \dot{q}. \quad (20)$$

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; $\dot{q} = dq / dt$ is the power of thermal effect of plastic deformation (friction).

Since the contact volumes of both materials of the friction pair (Fig. 1) are deformed, equations (19) and (20) should be rewritten as:

$$\omega_f = \Delta u_{e1} + \Delta u_{e2} + q_1 + q_2, \quad (21)$$

$$\dot{\omega}_f = \dot{u}_{e1} + \dot{u}_{e2} + \dot{q}_1 + \dot{q}_2. \quad (22)$$

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

The first part is related to variation of the latent (potential) energy (Δu_{e1} and Δu_{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 [2,3]. This is a measure of strain hardening and damage of material.

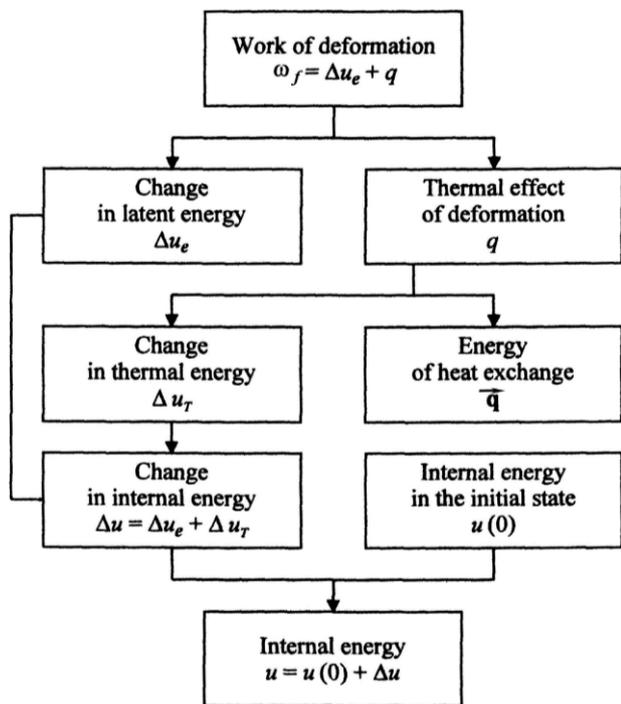


Fig. 1. Scheme of the energy balance for the plastic deformation of a solid body [2-6].

The second part of the friction work ω_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 Δu_{e1} and Δu_{e2} , as well as q_1 and q_2 are defined by physical-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 (Fig. 2), equations (21) and (22) can be rewritten in the form:

$$W_f = \Delta U_e + Q = \Delta U_{e1} + \Delta U_{e2} + Q_1 + Q_2, \quad (23)$$

$$\dot{W}_f = \dot{U}_e + \dot{Q} = \dot{U}_{e1} + \dot{U}_{e2} + \dot{Q}_1 + \dot{Q}_2, \quad (24)$$

where: $\Delta U_e = V_f \Delta u_e$; $\dot{U}_e = V_f \dot{u}_e$; V_f is the deformable (friction) volume.

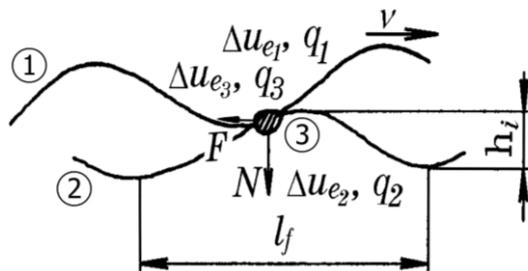


Fig.2. Schematic view of friction's contact [7].

Solving equations (23) and (24) for the frictional force F , one obtains:

$$F_l = \frac{\Delta U_{e1} + \Delta U_{e2}}{l} + \frac{Q_1 + Q_2}{l}, \quad (25)$$

$$F_v = \frac{\dot{U}_{e1} + \dot{U}_{e2}}{v} + \frac{\dot{Q}_1 + \dot{Q}_2}{v}, \quad (26)$$

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

Dividing equations (25) and (26) by the normal force N gives generalized equations for the friction coefficient:

$$\mu_l = \frac{\Delta U_{e1} + \Delta U_{e2}}{Nl} + \frac{Q_1 + Q_2}{Nl}, \quad (27)$$

$$\mu_v = \frac{\dot{U}_{e1} + \dot{U}_{e2}}{Nv} + \frac{\dot{Q}_1 + \dot{Q}_2}{Nv}. \quad (28)$$

Therefore, the friction is generally described by the energy balance equation and from the thermodynamical point of view [1-3] is the process of two interrelated, oppositely directed and concurrent trends operating in a strained contact.

Thus, the thermodynamic analysis of plastic deformation and fracture of solid makes it possible to derive the generalized (two-term) equations for friction force F and friction coefficient μ . This is in agreement with up-to-date understanding of friction. Denoting in (26) the friction component relating to storage of latent strain energy as F_{mech} and the friction component relating to thermal effect as F_{mol} we obtain the known relationships of molecular-mechanical [9] or deformable-adhesion [10] theories of friction.

$$F = F_{mech} + F_{mol} \cong F_{def} + F_{adh}. \quad (29)$$

Here:

$$F_{\text{mech(def)}} = \frac{\dot{U}_{e1} + \dot{U}_{e2}}{v} \quad (30)$$

$$F_{\text{mol(adh)}} = \frac{\dot{Q}_1 + \dot{Q}_2}{v} \quad (31)$$

Correspondingly, formulas (28) may be reduced to the form:

$$\mu = \mu_{\text{mech}} + \mu_{\text{mol}} \cong \mu_{\text{def}} + \mu_{\text{adh}} \quad (32)$$

Here:

$$\mu_{\text{mech(def)}} = \frac{\dot{U}_{e1} + \dot{U}_{e2}}{Nv} \quad (33)$$

$$\mu_{\text{mol(adh)}} = \frac{\dot{Q}_1 + \dot{Q}_2}{Nv} \quad (34)$$

But, it is more correct to speak about the adaptive-dissipative nature (model) of friction:

$$\begin{aligned} \mu &= \frac{\Delta U_{e1} + \Delta U_{e2}}{Nl} + \frac{Q_1 + Q_2}{Nl} = \mu_{\text{adapt}} + \mu_{\text{dis}} = \\ &= \mu_{\text{adapt}} + \mu_{T(\text{dis})} + \mu_{\bar{Q}(\text{dis})} \end{aligned} \quad (35)$$

Here: μ_{adapt} is adaptive friction coefficient; $\mu_{T(\text{dis})}$ and $\mu_{\bar{Q}(\text{dis})}$ are statical and dynamical components of dissipative friction coefficient.

As follows from equations (29) to (34), the friction force F and the friction coefficient μ show the dual (competitive) nature of friction, which is related to the growth of latent energy (Δu_{e1} and Δu_{e2}) of various defects and damages of structure and, accordingly, to strain hardening of the contact volumes (mechanical component of friction [9]), as well as to dynamic recovery (dissipation) of stored strain energy and thermal effect of friction q_1, q_2 (molecular component of friction [9]).

The formulas (25) to (28) establish the interrelation between microscopic parameters of friction $\Delta u_{e1}, \Delta u_{e2}, q_1, q_2$ and macroscopic external parameters N and v . The generalized relationships take into account both the characteristics of shaft material (counter body) $\Delta u_{e1}, q_1$ and that of bearing material $\Delta u_{e2}, q_2$.

For deformable rubbing surfaces, the energy relationships (23) to (28) are reduced easily to the well known equations of modern tribology. So, we may show as equation (6) is reduced to

the Coulomb equation. Denoting the friction component (31) by parameter B , attaching a meaning of adhesion characteristic to it, and representing equation (30) as:

$$\frac{\dot{U}_{e1} + \dot{U}_{e2}}{Nv} N = \mu_{\text{mech(def)}} N, \quad (36)$$

we obtain the Coulomb equation:

$$F = \mu N + B \quad (37)$$

In the case both the friction coefficient μ and the indeterminate parameter B have the certain meaning; the equation for friction force (26) is defined in terms of sliding velocity v and characteristics of both mating materials $\dot{u}_{e1}, \dot{u}_{e2}, q_1, q_2$.

Relationships (21) to (28), which generalize the mechanism of energy dissipation at friction, allow classifying the tribosystem states. According to egrodynamics of deformed solids (relationships $\Delta u = \Delta u_e + \Delta u_T$ and $\Delta u_T = q - \bar{q}$) equations (23) and (24) may be transformed to:

$$\dot{W}_f = \Delta U_{e1} + \Delta U_{e2} + \Delta U_{T1} + \Delta U_{T2} + \dot{Q}_1 + \dot{Q}_2, \quad (38)$$

$$\dot{W}_f = \dot{U}_{e1} + \dot{U}_{e2} + \dot{U}_{T1} + \dot{U}_{T2} + \dot{Q}_1 + \dot{Q}_2. \quad (39)$$

As follows from equations of energy balance (38) and (39), 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 (38) and (39), 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 of friction contact $\bar{q} = \bar{q}_1 + \bar{q}_2$.

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 [11]) and thermal damage and wear

(due to thermal activation [11]). 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 component Δu_e ($\Delta u = \Delta u_e$). Then, the mechanical damage and wear with brittle fracture of surfaces take place. On the contrary, if the potential component Δu_e is equal to zero and the internal energy variation at damage and wear is specified only by the thermal component ($\Delta u = \Delta u_T$), 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.

Finally, we would consider the basic notion of tribology – “third body” [9]. In the most general case, the energy balance at dry friction (23) should be written as:

$$W_f = \Delta U_{e1} + \Delta U_{e2} + \Delta U_{e3} + Q_1 + Q_2 + Q_3. \quad (40)$$

The equation considers the components ΔU_{e3} and Q_3 which define the deformed contact with account for generation and existence of the “third body”. In the special case, when the friction is localized into volume of the “third body” (Fig. 2), equation (40) develops into:

$$W_f = \Delta U_{e3} + \bar{Q}_3. \quad (41)$$

Here: $\Delta U_{e3} = V_3 \Delta u_{e3}$.

According to thermodynamic theory [2], 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 macro volume that is responsible for fracture.

4. 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 Δu_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 (25) to (28) that the Amontons (Leonardo da Vinci) friction coefficient is:

$$\mu = \frac{\Delta U_e}{\mu^* N l} = \frac{F}{N}, \quad F = \frac{\Delta U_e}{l}, \quad Q \cong 0, \quad \mu^* = 1. \quad (42)$$

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, since it defines 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 as the energy of defects and damages of different types, that are accumulated into contact volumes of solids V_f .

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.

5. GENERALIZED EXPERIMENTAL FRICTION CURVES

The dependences obtained for the friction coefficient μ are in agreement with experimental curves $\mu = \mu(N, v)$, Figs. 3, 4 and 5.

A subsequent analyses of modern experimental data using equations (23) to (28) has shown that the experimental friction curves (Figs. 3, 4 and 5) of type $\mu = \mu(N, v)$ are generalized friction curves that reflect the evolution (the change in the friction coefficient) of tribosystem.

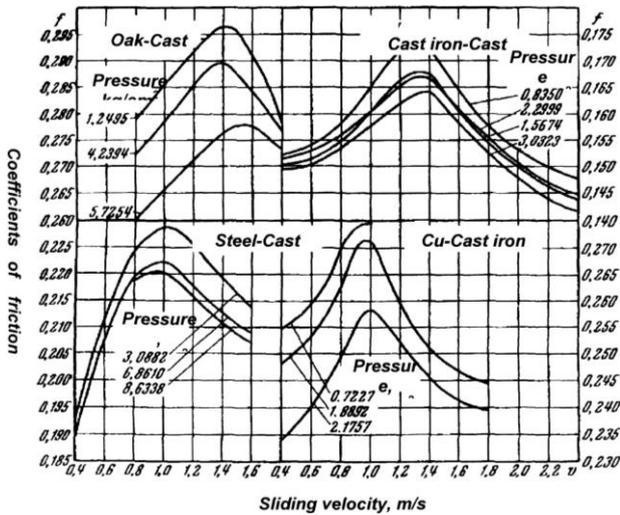


Fig. 3. P. Conti's experimental results [12].

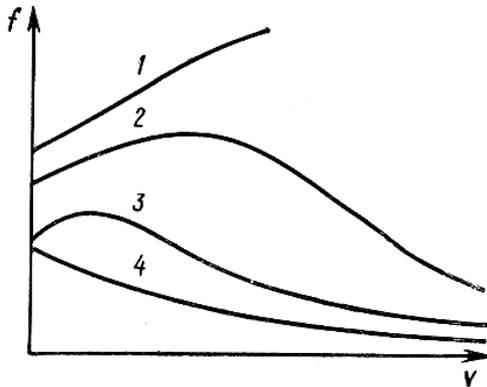


Fig. 4. Generalized friction experiments in Kragelsky's interpretation: v – sliding velocity; load: 1 – small, 2 and 3 – medium and 4 – considerable.

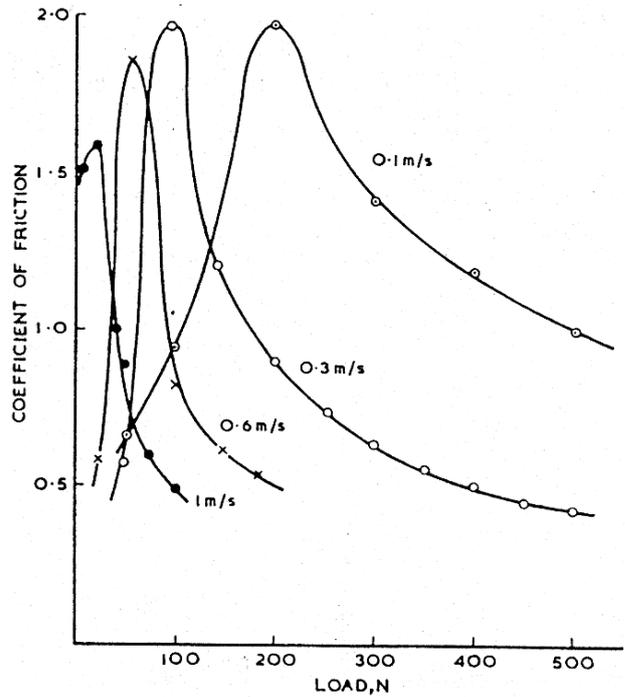


Fig. 5. Watanabe's [13] experimental results of Nylon 6 – steel pair of friction.

6. STRUCTURAL ENERGY DIAGRAM FOR EVOLUTION OF RUBBING SURFACES

It is proposed an energetic interpretation of the experimental friction curves $\mu = \mu(N, v)$ in view of structural-energy diagram for evolution of rubbing surfaces (Fig. 6).

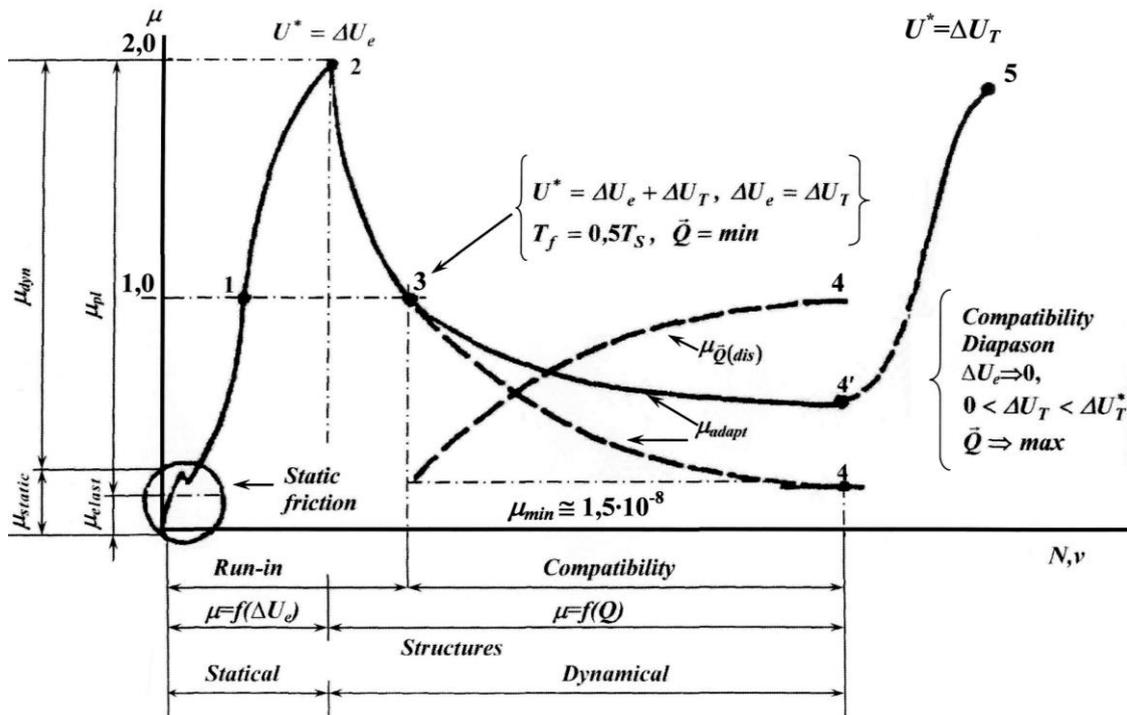


Fig. 6. Structural-energy diagram for evolution of rubbing surfaces [1,14].

Evolution of tribosystem, presented as a diagram view (Fig. 6), has an adaptive-dissipative character (23) to (28) and (35), and reflects the competitive (dialectical) nature of friction. Evolution curve has the row of principal points (1-5) of transitional tribosystem states [1], 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 6 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 self-organization; 3-4': a stage of compatibility; 4: a point of wearlessness (anormal-low friction); 5: a point of thermal adhesion.

The assignment of the points on the friction curve is somewhat arbitrary and depends on the nature and structural properties of the materials and the frictional (environmental) conditions.

The energetic analysis of the experimental friction curves $\mu = \mu(N, v)$ [1,14] has shown that each characteristic point can be related to the latent energy change ΔU_e within the deformable (contact) volumes of an evolutionary (adaptive) tribosystem.

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

In the most general case, evolution (adaptation) regularities of tribosystems may be presented as a V_2 stage (Fig. 6). 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 the elementary tribosystem, which is the elementary and self-sufficient energy transformer. The first stage: latent energy

density growth Δu_e to a limited magnitude Δu_e^* within critical friction volume V_f^* .

This friction volume V_f^* is constant at the second stage of evolution, but here, it is evolutionary developed owing to structural transformation; by this one may realize wide spectrum of compatibility friction structures (Fig. 6). The second stage (2-4): structural transformation of critical friction volume (elementary tribosystem) V_f^* into adaptive V_{adapt} and dissipative V_{dis} volumes. The limit (point 4) of this stage is characterized by a full transformation of adaptive critical volume V_{adapt}^* into V_{dis}^* dissipative.

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

Suggested theoretical and calculation assessments [1,14] showed that dissipative friction volume performs reversible elastic energy transformation of outer mechanical movement with density \bar{q}^* equal to critical density of latent energy u_e^* .

$$W_f = \Delta u_e^* V_{adapt} + \bar{q}^* V_{dis} \cdot \quad (43)$$

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

7. CONCLUSION

As a model of friction we can examine a model of elastic-plastic deformation. Elastic-plastic deformation model in its energy interpretation makes it possible to consider the transformative process of friction. Indeed, such a model of

plastic deformation is the main mechanism of energy dissipation by friction. Therefore, the energy balance of the deformation is the energy balance model of friction. In this case, structural energy (adaptive-dissipative) model of friction within the energy-balance equations of friction corresponds to the modern notion of friction as an ambivalent phenomenon. The friction should be treated as dialectic phenomenon with competitive trends. The first trend relates to the microscopic processes of accumulation of latent (potential) energy of various structural defects and damages. The second trend is the microscopic processes of relaxation and thermal effect. Structural-energy model of friction allows us to offer an energetic interpretation of the coefficient of friction. This interpretation introduces the coefficient of friction as the most informative characteristics of friction. Energy model of the coefficient of friction is convenient for the analysis of generalized regularities of evolution states and properties for the tribosystem (contact volume).

REFERENCES

- [1] S.V. Fedorov, *The Foundations of Triboergodynamics and Physico-Chemical Prerequisites of Compatibility Theory*. Kaliningrad: Kaliningrad State Technical University Press, 2003 [in Russian].
- [2] V.V. Fedorov, *Thermodynamic Aspects of Strength and Fracture of Solids*. Tashkent: Science, 1979 [in Russian].
- [3] V.V. Fedorov, *Kinetics of Damage and Fracture of Solids*. Tashkent: Science, 1985 [in Russian].
- [4] V.V. Fedorov, 'Ergodynamic concept of strength and failure of solids', in *Proceeding of the VI-th All-Union Congress on Theoretical and Applied Mechanics*, 1986, Tashkent, USSR, pp. 610-611 [in Russian].
- [5] V.V. Fedorov, 'Ergodynamic and synergetic of deformed solids', *Physico-Chemical Mechanics of Materials*, no. 1, pp. 32-36, 1988 [in Russian].
- [6] V.V. Fedorov, 'Ergodynamic concept of failure', *Strength of Materials (Translated from Russian)*, vol. 23, no. 8, pp. 883-889, 1991.
- [7] V.S. Ivanova, *Fatigue Fracture of Metals*. Moscow: Metallurgy, 1963 [in Russian].
- [8] J. Friedel, *Dislocations*. Oxford, 1964.
- [9] I.V. Kragelskii, M.N. Dobyclun, and V.S. Kombalov, *Friction and Wear Calculation Methods*. Moscow: Mechanical Engineering, 1977 [in Russian].
- [10] F.P. Bowden and D. Tabor, *The Friction and Lubrication of Solids*. Oxford: At the Clarendon Press, 1964.
- [11] B.I. Kostetskii, *Friction, Lubrication and Wear in Machines*. Kiev: Technics, 1970 [in Russian].
- [12] I.V. Kragelskii and V.S. Schedrov, *Development of Science of Friction*. Moscow: USSR Academie Science, 1956 [in Russian].
- [13] I.K. Lancaster, 'Basic mechanisms of friction and wear of polymers', *Plastics and Polymers*, vol. 41, pp. 296-306, 1973.
- [14] S.V. Fedorov, 'Energy Model of sliding friction coefficient and generalized regularities of tribosystems evolution', in *Transactions of the 19th International Colloquium Tribology "Tribology-Industrial and Automotive Lubrication"*, TAE, 21-23.01.2014, Esslingen, Germany.