ISSN 1068-3666, Journal of Friction and Wear, 2024, Vol. 45, No. 2, pp. 107–114. © Allerton Press, Inc., 2024.
Russian Text © The Author(s), 2024, published in Trenie i Iznos, 2024, Vol. 45, No. 2, pp. 160–170.

In memory of Professor Vasily Vasilyevich Fedorov

On the Structural Superplasticity of the Third Body According to the Model of a Mechanical (Nano) Quantum

S. V. Fedorov*

Kaliningrad State Technical University, Kaliningrad, 236022 Russia

**e-mail: fedorov@klgtu.ru*

Received December 4, 2023; revised April 12, 2024; accepted April 17, 2024

Abstract—The phasing of the friction process provides for the formation of the intersurface phase of the rubbing surfaces of the friction pair, the "third body". In essence, the third body is a hinge of internal friction of a developed stage of joint plastic deformation of surfaces. Being a consequence of the self-organization of surface adaptation processes in the presence of environmental chemistry, the third body can have a wide range of tribological properties. These properties, in turn, are a consequence of the formation of a wide range of optimal (compatible) structures of the third body, which determines the controllability of friction. The relationship of structure and properties as the basic principle of tribomaterial science provokes the question of what are the limits of this relationship? For example, what are the minimum properties of friction and how are they reflected in the essence of the structural structure and behavior of the friction contact? The equation of a quasi-ideal solid third body under friction is obtained, which proves the existence of an elementary structural element of a solid body under friction (deformation), a mechanical (nano) quantum. A mechanical quantum, as an ideal (theoretical) crystal of atomically rough and spherical shape, is an oscillator of dynamic dissipative friction structures. The potential energy accumulated initially during the evolution of contact is further dissipated in the area of compatibility into these formed mechanical quanta of the third body (elementary tribosystem) in the form of surface energy, creating prerequisites for their elastic reversals with an abnormally low coefficient of friction between them. The efficiency of the third body is proportional to the spectrum of elastic reversals of structural shapes.

Keywords: friction, evolution, elementary tribosystem, third body, compatibility, dissipative structures, mechanical quantum, superplasticity

DOI: 10.3103/S1068366624700168

INTRODUCTION

Friction is an evolutionary phenomenon of adaptation of two surfaces during their relative movement to the level of external influence, which proceeds according to the laws of self-organization, in the direction of minimizing the action of generalized external forces. When friction occurs, the contact changes its state and properties. As a result of the evolution of friction contact, a transition from external friction to internal friction occurs. In this case, a critical volume of friction is formed (an elementary tribosystem), which operates in the form of a moving hinge of deformation, a hinge of internal friction. Here, this transition from isolated deformation of surfaces to their joint deformation in tribology is associated with the fundamental concept of the "third body" [1]. With the mutual movement of bodies, destruction and at the same time the formation of this third body occurs. Actually, this third body, a deformation hinge that appears after running-in in the compatibility region, is at the same time adequate to the concept of secondary friction structures [2].

The parameters of friction (shear stress) and wear as structure-sensitive characteristics, taking into account the nature of the formation of the third body or secondary friction structures, can have a wide range of values.

Actually, today we understand that this new formation (third body) of jointly deformed surfaces should be considered as the effect of the formation of a self-organized solid lubricant [3].

Extensive studies of tribology, summarized by a diagrammatic view of the structural-energy evolution of rubbing surfaces (Fig. 1 [4]), indicate the fact of the formation of dynamic dissipative friction structures after running-in (transition through a highly excited state of contact). The latter structures have the property of structural superplasticity. What are the limits of this superplasticity under friction?

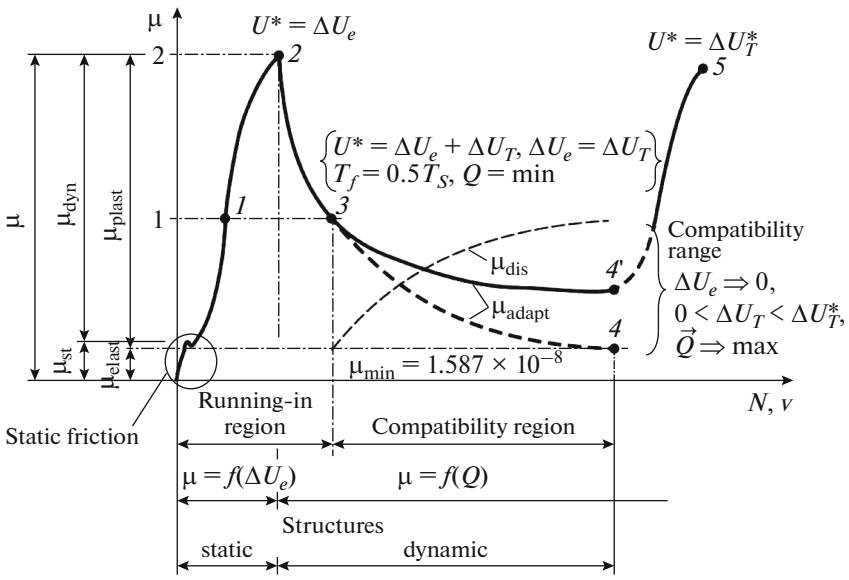

Fig. 1. Structural-energy diagram of the evolution of rubbing surfaces (friction contact) [4]. Designation on the axes: N, v are load and speed; $\mu_{st}, \mu_{dyn}, \mu_{elast}, \mu_{plast}$ are static, dynamic, elastic, plastic friction coefficients; T_f, T_S are temperature point in the contact volume of friction at point 3 and melting temperature.

Today, within the framework of formalizing the mechanism of structural superplasticity, there are several opinions [5–7]: intergranular sliding (grain boundary deformation); sphericity of structural elements; elastic structural reversals of developed plastic deformation; and temperature range of structural superplasticity not lower than $0.5T_S, K$.

Objective—To consider the general patterns of structural and energy evolution of friction contact; identify the state of the ideal thermodynamic cycle at the friction contact; and consider the features of the structural state of the third body during its most complete evolution.

SETTING TASKS. TO THE EQUATION OF A QUASI-IDEAL RIGID BODY

In thermodynamics, the equation of state of an ideal gas is known, connecting pressure, volume, and temperature, this is known as the Clapeyron equation:

$$\frac{pV}{T} = \text{const}. \tag{1}$$

It has been repeatedly suggested [8, 9] that a similar mechanical equation of state should exist for solid deformable bodies.

In this matter, it is advisable to analyze the general structural and energy patterns of the evolution of states and properties of systems with friction, tribosystems (Fig. 1), performed using the generalized (thermodynamic) method [3, 4].

In Fig. 1 you can see: *0–1*—area of static friction and strain (dislocation) hardening; *1*—point of limiting strain hardening; *1–2*—region of pumping excess energy of vacancies; *2*—point of setting and transition of external friction to internal (critical instability); *2–3*—region of formation of dissipative structures (formation of temperature fluctuations in the friction volume); *3*—point of minimum compatibility (maximum friction); *1–2–3*—area of self-organization; *3–4*—area of compatibility; *4*—point of wearlessness (abnormally low friction); *5*—thermal setting point.

The friction energy balance equations [4] are considered as generalized equations of compatibility of rubbing surfaces, since they essentially describe the joint work (deformation) of the surfaces of a friction pair; for the friction coefficient they have form:

$$\mu = \frac{\Delta U_{e\Sigma}}{Nl} + \frac{Q_\Sigma}{Nl} = \frac{\Delta U_{e\Sigma}}{Nl} + \frac{\Delta U_{T\Sigma}}{Nl} + \frac{\vec{Q}_\Sigma}{Nl} = \mu_{adapt} + \mu_{dis} = \mu_{adapt} + \mu_{dis_T} + \mu_{dis_{\vec{Q}}}, \tag{2}$$

$$\mu = \frac{\dot{U}_{e\Sigma}}{Nv} + \frac{\dot{Q}_\Sigma}{Nv} = \frac{\dot{U}_{e\Sigma}}{Nv} + \frac{U_{T\Sigma}}{Nv} + \frac{\dot{\vec{Q}}_\Sigma}{Nv} = \mu_{adapt} + \mu_{dis} = \mu_{adapt} + \mu_{dis_T} + \mu_{dis_{\vec{Q}}}. \tag{3}$$

Here, μ_{dis_T} and $\mu_{dis_{\vec{Q}}}$ are static (temperature—slow) and dynamic (temperature-free—fast) components of energy dissipation of the friction coefficient. As follows from the structural-energy diagram of the evolution of rubbing surfaces (Fig. 1), critical friction volume V_f^* (elementary tribosystem) in the compatibility area consists of two volumes, adaptive V_{adapt} and dynamic dissipative V_{dis}. The adaptive volume is responsible for damage and wear, the dynamic dissipative volume is responsible for

the reversible return of energy (supporting external movement at the internal level).

The friction energy balance equation (2) for the dissipative friction coefficient in the compatibility region and for the compatibility range (see Fig. 1) can be written as:

$$\mu_{\text{dis}_{\vec{Q}}} = 1 - \mu_{\text{adapt}} = -\frac{\vec{Q}}{Nl}. \quad (4)$$

Considering that initial temperature $\overline{T}$ in the compatibility region (point *3* in Fig. 1) on the oscillator (adaptive volume) is constant (isothermal process $0 \le \Delta u_T \le u^*$) and equal $0.5T_S$ or T_S (if the calculation is related to the volume size of the equilibrium roughness) [4], then, by relating the amount of reversibly dissipated energy $\vec{Q}$ to temperature $\overline{T}$, we obtain in the compatibility region the condition for the growth of inertial entropy $\vec{S}_Q$ (decrease in configuration entropy S_U) from point *3* towards stability point *4* (wear-free):

$$\Delta\vec{S}_Q = \frac{\Delta\vec{Q}}{T}, \quad (5)$$

that is, in this case, the entropy of dynamic scattering of each point of the curve (points *3*–*4*) (see Fig. 1)) is proportional $\mu_{\text{dis}_{\vec{Q}}}$ or $1 - \mu_{\text{adapt}}$:

$$\vec{S}_Q = \frac{\vec{Q}}{T} = \frac{\mu_{\text{dis}_{\vec{Q}}} Nl}{T} = \frac{(1 - \mu_{\text{adapt}})\, Nl}{T}. \quad (6)$$

Therefore, from a physical point of view, friction coefficients $\mu_{\text{dis}_{\vec{Q}}}$ and μ_{adapt} act as parameters of order (disorder) of the tribosystem. The relationship between order O and disorder D can be represented by the relation: O = 1 – D.

Comparing this expression with equation (4), we obtain

$$\text{O} = \mu_{\text{dis}_{\vec{Q}}}, \quad \text{D} = \mu_{\text{adapt}}. \quad (7)$$

Thus, the true coefficient of friction μ_{adapt}, ($\mu_{\text{dis}_{\vec{Q}}}$) from a physical point of view is a structural parameter of the tribosystem state.

From equation (6) follows an expression that allows us to consider the physical meaning of the concept of entropy $\vec{S}_Q$, namely, taking into account that in the dissipative volume V_{dis} dissipation energy density $\vec{q}_*$ equal to the critical latent energy density u_e^* [4] we get

$$\vec{S}_Q = \frac{\vec{Q}}{T} = \frac{\vec{q}_* V_{\text{dis}}}{T} = \frac{u_e^* V_{\text{dis}}}{T}. \quad (8)$$

Since in equation (8) the relation $u_e^*/T = \text{const}$, we obtain that the physical meaning of entropy as an order parameter is associated with a change in volume V_{dis} (volume of dynamic dissipative structures), which has the ability to reversibly dissipate (return) the energy of external mechanical motion.

If we represent equation (6) in the form

$$\vec{S}_Q T = \mu_{\text{dis}_{\vec{Q}}} Nl, \quad (9)$$

then by analogy with the equation of state for gases $PV = \mu RT$, equation (9) can be called the equation of state of the tribosystem (deformable body). At $\mu^*_{\text{dis}_{\vec{Q}}} = 1.0$ (condition of elastic dissipative contact) this equation turns into the equation of a quasi-ideal solid body

$$\vec{Q}^* = \vec{S}_Q T = \mu^*_{\text{dis}_{\vec{Q}}} Nl = V_f^* u_e^* = V_f^* \vec{q}_*. \quad (10)$$

Consequently, under conditions of maximum compatibility, when the tribosystem implements the full evolutionary cycle of adaptation with the formation of the most perfect, dissipative structure, its (structure) behavior obeys the equation of state of a quasi-ideal solid body, that is, it should be assumed that the interactions between the elements of this structure are minimized—a state of ideal elasticity (see (1)).

Theoretical and computational analysis [4] of energy transformation by an elementary tribosystem (deformable contact) shows (Fig. 1) that the ideal evolution of a tribosystem (material point) begins and ends in elastic regions, between which there is a complete transformation cycle of the evolution of the plastic (irreversible) friction component with point 2 of the highly excited state of area 1–2–3 of self-organization. With ideal evolution of the tribosystem, the adaptive (Amonton) friction coefficient μ_{adapt} beyond point 2 of the diagram it drops sharply, reaching the value of the elastic friction coefficient μ_{elast} (point 4), that is

$$\mu^{\min}_{\text{adapt}} = \mu^* - \mu^{\max}_{\text{dis}} = 1 - \mu^{\max}_{\text{dis}} = \mu_{\text{plast}} = 0 = \mu_{\text{elast}}. \quad (11)$$

At the same time, it was shown [4] that the value of the minimum adaptive friction volume $V^{\min}_{\text{adapt}}$, corresponding to the zero value of the plastic friction component $\mu^{\min}_{\text{adapt}}$, is not equal to zero, but is equal to the size of some smallest structural formation corresponding to the state of ideal elasticity at the contact.

ON THE ENERGY SIZE OF A TRIBOSYSTEM

Equation (10) 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, is reduced to the form

$$\mu_{\text{dis}_{\vec{Q}}} = \frac{\vec{S}_Q T}{Nl} = \frac{kTN_f \ln W}{Nl}, \quad (12)$$

$$\mu_{\text{adapt}} = 1 - \mu_{\text{dis}_{\vec{Q}}} = 1 - \frac{kTN_f \ln W}{Nl} = 1 - \frac{\vec{S}_Q T}{Nl} = \frac{S_U T}{Nl}. \quad (13)$$

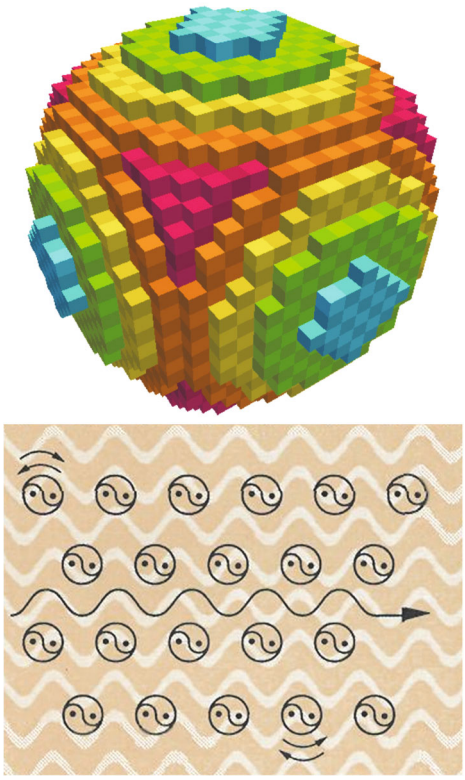

Fig. 2. A model of an ideal crystal of an elementary nanostructure of a friction contact [3, 4] and a nano-quantum structure of a "third body" with an ideal evolution of the friction contact.

These equations (12), (13) explain the laws of friction from the point of view of its evolution. According to these equations, the tribosystem always tends to some optimal state, characterized by μ_{adapt}, that is, to the most probable state $W' = N_f \ln W$ for given friction conditions.

Reducing the coefficient of friction μ_{adapt} and growth of the coefficient $\mu_{dis_{\bar{Q}}}$ When the tribosystem reaches a stationary friction mode (see Fig. 1), it tends to the most probable (optimal) state.

On the other hand, from equations (12), (13) it follows that if the probability of the state is constant W, the desire of a tribosystem to an optimal state is associated with an increase in the proportion of atoms (oscillators) N_f, taking part in the dissipation (reversible return) of energy Nl_f. Fully compatible $V_{dis} = V_f^*$, all atoms of critical volume V_f^* equally excited to the maximum and therefore no energy accumulation occurs Δu_e, and there is a reversible "transit" transformation of the energy of external mechanical movement.

The probability value of the state was determined [3, 4] W tribosystems:

$$\ln W = 3. \qquad (14)$$

It follows that the value W, is equal $\mathbf{e}^3 = 20.08553696$.

Thus, the probability value of the state W is constant throughout the entire range of compatibility (Fig. 1) and is equal to 20.08553696. Consequently, this once again confirms the conclusion of formula (8) that the inertial entropy $\vec{S}_Q$ is proportional to the size of the volume that reversibly dissipates (returns) the energy of external mechanical motion.

However, according to Boltzmann, entropy S must be related to the thermodynamic probability of the state W. For such a connection to actually take place, you just need to multiply the number k by the amount N_f is the number of atoms in the friction volume (elementary tribosystem) V_f^*. Then, by analogy with the universal gas constant $R = kN_A$ (Here N_A is Avogadro's number), we obtain the universal friction constant (of deformable volume)—$R_f = kN_f$. Now in equation (12) the entropy $\vec{S}_Q$ will indeed be related to the thermodynamic probability of the state W. The maximum value of the thermodynamic probability of the tribosystem state W^* accordingly determined by the value of the coefficient $\mu_{dis_{\bar{Q}}} = 1.0$, and vice versa, the minimum value W_{min} proportional to the minimum coefficient value $\mu_{dis_{\bar{Q}}}^{min}$.

In physical meaning, the universal friction constant $R_f = kN_f$ (J/(K TS)) characterizes the energy size of an elementary tribosystem (TS). Consequently, the size of the elementary tribosystem (1 TC) is determined by volume V_f^*—a volume containing the same number of atoms N_f.

ON THE MECHANICAL QUANTUM OF DISSIPATIVE FRICTION STRUCTURES

Thermodynamic probability number of a state W, equal to 20.08553696 was interpreted [3, 4] as the smallest number of linear oscillators in one of the three directions of the minimum adaptive friction volume V_{adapt}^{min}, corresponding to a state of almost absolutely elastic friction – abnormally low friction (safe deformation threshold). Accordingly, the number of atomic oscillators in this volume is equal to $W^3 = (\mathbf{e}^3)^3 = 20.08553696^3 = 8103.083969$.

The size of the minimum adaptive friction volume, V_{adapt}^{min} its value coincides with the size of the submicroscopic zone at the crack mouth [10], which for metals is equal to $(4–9)\times 10^{-6}$ mm, that is, with the size of the critical volume responsible for destruction. Thus, the size of the minimum adaptive volume $V_{adapt}^{min} = V_{elast}$, can be represented as the size of a certain mechanical "Quantum" (Fig. 2). This mechanical quantum represents the minimum number of atoms capable of providing such a configurational distribution (structure)

that has the property of reversibly receiving and dissipating (returning) the energy of external mechanical motion (impact). It also represents the smallest structural formation of a solid body under conditions of plastic deformation and is formed during the transition of the tribosystem (deformable volume) through an extremely activated (critical) state (Fig. 1), due to the development of self-organizing adaptation processes of the tribosystem.

The conclusion that a mechanical quantum is the smallest structural formation during plastic deformation (friction) is confirmed by calculations. If we compare the values of the elastic moduli E, to atomic (true) elasticities E_r [4], then we get values equal to 60, where the number $60 = 3W$ can be interpreted as a characteristic of volumetric elasticity (state) of one mechanical quantum—the minimum adaptive volume of friction $V_{\text{adapt}}^{\min}$. Calculated parameter estimate $W \cong 20 = E/3E_r = E/u_e^*$, performed for various metals and steels, is presented in Table 1.

This fact can be taken as an explanation of the reason for the discrepancy between the theoretical atomic elasticity E_r (strength) and real experimental elasticity E (strength), which, in essence, is a macroscopic characteristic of the manifestation (probability) of volumetric elasticity of one mechanical quantum—$E = 3WE_r = W\Delta H_S$.

Since the value $V_{\text{adapt}}^{\min}$ is the magnitude of the volume of elastic static interaction of surfaces, then, therefore, with any elastic critical interaction of surfaces, including with any rupture (destruction), when the formation of surfaces takes place, it is necessary to reversibly expend (or reversibly return to the environment) an amount of energy in magnitude, equal to the energy of one mechanical quantum.

MODEL OF NANO-QUANTUM DAMPING OF SURFACES UNDER COMPATIBILITY CONDITIONS

The lower the friction coefficient μ_{adapt} (large coefficient value $\mu_{\text{dis}_{\ddot{Q}}}$) is characterized by a tribosystem, the higher its fatigue endurance (durability), since a larger number of mechanical quanta are involved in the process of damping (elastic return) of the energy of external mechanical movement (impact), and, consequently, a smaller number of quanta are associated with destruction (accumulation of latent energy of defects and damage of maximum magnitude). In the limit, the tribosystem is characterized by the effect of "wearlessness" (abnormally low friction), corresponding to the state of almost complete thermodynamic reversibility of the friction (deformation) process. In this case, all mechanical quanta, with the exception of one, reversibly and elastically transform (dampen) the energy of external mechanical motion.

Table 1. Parameter estimation W for various metals and steels [4]

Metal and steel	$E \times 10^{-3}$, MPa	$(u_e^*)\Delta H_S \times 10^{-3}$, MJ/m^3	$E/3E_r$
Cr	235.4	8.5	27.69
Mg	44.4	1.9	23.37
Ag	79.0	3.7	21.35
Au	78.7	4.0	19.67
Co	200.1	10.6	18.88
Fe	211.4	9.9	21.35
Ta	184.4	10.6	17.39
Ti	105.9	6.7	15.80
Nb	104.0	9.2	11.30
Zr	95.6	5.7	16.77
Mo	316.9	12.0	26.40
W	392.4	14.4	27.25
Ni	201.1	9.5	21.06
Iron	210.9	10.1	20.88
Article 20	200.1	9.5	21.06
1X13	206.0	8.9	23.14
3X13	218.8	9.2	23.78
H18N9T	199.1	9.4	21.19
X18M9	199.1	9.6	20.74
30X	214.1	10.2	20.99
30H3	207.5	10.3	20.10
Article 40	209.4	9.7	21.58
30G2	207.2	10.0	20.72
30 XGN3	208.0	10.2	20.40
G13	204.0	10.0	20.40
50C2G	196.2	10.3	19.05
U8	198.0	10.3	19.22
U12	198.0	10.4	19.04

$\Delta H_S = 3E_r\ (\overline{E/3E_r}) = 20.77$.

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

Thus, the minimum mechanical interaction of surfaces cannot be realized by a number less than one mechanical quantum. One quantum of radiation (8103, ... atoms) is the minimum loss (the essence of wearlessness) and the standard of wear.

Considering these representations as a model of quantum damping of surfaces, equations (12) and (13) can be represented as

$$\mu_{\text{dis}_{\bar{Q}}} = \frac{3R_{MQ}Tn_i}{Nl} = \frac{U_{1Q}n_i}{U_{1Q}n_*} = \frac{n_i}{n_*} = 1 - \mu_{\text{adapt}}, \quad n_i = n_* - n_{\text{dest}\,t}, \tag{15}$$

$$\mu_{\text{adapt}} = 1 - \frac{n_i}{n_*} = \frac{n_{\text{dest}}}{n_*}, \tag{16}$$

where $R_{MQ} = k \times 8103.083...$, $\text{J}/(\text{K}\,MQ)$ is universal constant of mechanical quantum (MQ); $3R_{MQ}T = U_{1Q}$ is energy of one mechanical quantum; n_i is fatigue number, that is, the number of mechanical quanta damping the process; n_* is safe number of fatigue; n_{dest} is number of mechanical quanta of destruction.

Since the mechanical quantum itself is a dynamic oscillator of dissipative friction structures, its linear size [3, 4] can be determined by the radius of a spherical atomically rough ideal crystal:

$$D_Q = 2R_{MQ} = 2\sqrt[3]{\frac{3W^3\overline{d}_a^3}{4\pi}} = 2\sqrt[3]{\frac{3(\mathbf{e}^3)^3\overline{d}_a^3}{4\pi}} = 7.177 \text{ nm}. \tag{17}$$

Here $\overline{d}_a$ is average atomic diameter for metallic materials.

In [10], it was shown that for 65G steel the size of the submicroscopic fracture zone a_0 varies within $(5.5–8.8) \times 10^{-6}$ mm and on average equal to 7.15 nm. The calculated universal size of the mechanical quantum is 7.177 nm.

The spherical shape of an ideal crystal is the only possible formation that determines its oscillating (reciprocating) behavior in conjunction with other such oscillators in the volume of an ideally structured elementary tribosystem. On the other hand, the spherical and compact shape of a mechanical quantum is due precisely to the equilibrium state of this smallest structure during plastic deformation, when the values of the surface and internal energies are equal.

Actually, a mechanical quantum should be considered as an elementary nanostructure of a metallic solid deformable body or a tribosubsystem of an elementary tribosystem.

In the volume of an elementary tribosystem, the number of such mechanical quanta (tribosubsystems) is approximately equal to $n_* = 0.63 \times 10^8$ [3, 4], that is, the safe threshold of fatigue.

The size of an elementary tribosystem is determined by a universal constant:

$$R_f = kN_f = kW^3N_Q = R_{MQ}N_Q, \frac{\text{J}}{\text{grad TC}}. \tag{18}$$

Here R_{MQ}, R_f are universal constants of one mechanical quantum and an elementary tribosystem; k is Boltzmann constant; N_f is the number of atoms in the volume of an elementary tribosystem; N_Q is the number of mechanical quanta (tribosubsystems) in one elementary tribosystem.

Consequently, for all materials, under conditions of ideal tribosystem evolution, the number of atoms (mechanical quanta (MQ)) in the volume of one elementary tribosystem (TC) is a constant value. Thus, we can talk about an amount of substance equal in mass to one elementary tribosystem (one mechanical quantum).

The mechanical quantum principle determines the nano-quantum levels of all friction parameters of compatible tribosystems. Compatible tribosystems [4] have nano-quantum wear values.

SYNERGY OF THE TRIBOSYSTEM AND OPTIMAL STATE OF THE DEFORMABLE FRICTION CONTACT

The ideal, quasi-elastic state of the contact during its full evolution is the effect of the most complete dissipation of the energy of external mechanical motion along the newly formed (according to the self-organization mechanism in the vicinity of point 2 (Fig. 1)) structural elements—mechanical (nano) quanta (dynamic oscillators). Mechanical quanta can be considered as theoretical crystals of spherical shape (ideal fractal), which interact with each other, realizing the most complete scheme of their joint vibrational-rotational behavior relative to each other in the volume of an elementary tribosystem. At the same time, the resistance to their relative interaction is minimal—elastic and corresponds to the elasticity of ideal atomic (thermodynamically equilibrium) interactions at the level of electronic shells. The calculated value of the friction coefficient between mechanical quanta is approximately—$\mu_{MQ} = 1.587 \times 10^{-8}$ [3, 4].

Accordingly, the physical and quantitative patterns of the formation of dissipative structures of compatible friction, which have a durability proportional to the number of loading cycles $(1–0.63 \times 10^8)$ of an elementary tribosystem to the limiting state [4]. In the region of the compatibility range (Fig. 1), there is a set of discrete levels of compatible friction that obey the nano-quantum model of surface damping. These nano-quantum levels differ in the degree of energy dissipation along the structural elements of dissipative structures, which have an increasing degree of fractal-geo-

metric perfection, towards the point of ideal-elastic (abnormally low) friction (i.e. *4'*).

Considering the principle of nano-quantum levels L_n compatible friction, the degree of perfection of dissipative friction structures in the area of compatibility can be assessed by comparing the rotations of structural elements in proportion to the full revolution (oscillation) of a mechanical (nano) quantum, that is $360^\circ/L_i = \phi_i^\circ$ is elementary fractal (apparently according to a disclination [11] (rotational [12]) mechanism) angle of rotation of structural elements during quasi-viscous, elastoplastic deformation of the friction volume.

Thus, we can talk about synergism [4] during the evolution of friction, which manifests itself in the emergence of truly new properties in the whole, an elementary tribosystem formed in point *2*—the center of self-organizational processes. These new properties are the essence of a collective, truly joint, interaction of a set of mechanical (nano) quanta, including *4'* ideal evolution of the tribosystem. Nano-quanta as tribosubsystems in their elastic interaction realize the highest compatibility of tribomaterials (structural superplasticity) and, accordingly, the maximum durability of the elementary tribosystem.

CONCLUSIONS

(1) Thermodynamic analysis of the friction process and interpretation of the structural-energy evolution of the friction contact shows that after the running-in of two surfaces, a "third body" is formed—a hinge of joint elastoplastic deformation of the surfaces.

(2) This local hinge of developed elastoplastic deformation is an elementary tribosystem, functionally and structurally characterized by dynamic dissipative properties.

(3) The potential energy accumulated initially during the evolution of the contact is then dissipated in the compatibility region into the newly formed structural elements of the "third body" (elementary tribosystem), creating the prerequisites for their elastic reversals.

(4) Nominally, this effect of dynamic structural dissipation of accumulated energy manifests itself during the ideal evolution of a friction contact (elementary tribosystem) in the form of a huge set (~63 million) of ideal structural elements—mechanical (nano) quanta.

(5) Mechanical quanta as ideal (theoretical) crystals (grains) of a spherical atomically rough shape, mutually and rotationally reciprocating elastically oscillating with each other, essentially represent a model of ideal structural superplasticity of a third body (elementary tribosystem).

(6) Dynamic dissipative friction structures, having a wide range of structural perfection in the compatibility area and, accordingly, varying degrees of their elastic reversals, characterize the effect of the contact implementing the principle of self-organized solid lubrication with a wide range of quantitative antifriction properties.

ABBREVIATION AND NOTATION

p	pressure
V	volume
T	thermodynamic temperature, K
μ	coefficient of friction
μ_{adapt}	adaptive component of the coefficient of friction
μ_{dis}	dissipative component of the coefficient of friction
N	normal load
l	friction path
v	sliding speed
$\Delta U_{e\Sigma} = \Delta U_{e1} + \Delta U_{e2}$ and $\dot{U}_{e\Sigma} = \dot{u}_{e1}V_{f1} + \dot{u}_{e2}V_{f2}$	change and rate of change of the accumulated latent (potential) energy in the contact volumes of the friction pair
ΔU_{e1}, ΔU_{e2}, ΔU_{T1}, ΔU_{T2}	changes in latent (potential) and thermal (kinetic) components of internal energy in the contact volumes of shaft (1) and bearing (2) materials
$Q_\Sigma = Q_1 + Q_2$ and $\dot{Q}_\Sigma = \dot{Q}_1 + \dot{Q}_2$	thermal effect of friction and its power
$\vec{Q}_1$, $\vec{Q}_2$	dynamic dissipative effects in contact volumes of shaft and bearing materials
S_U, $\vec{S}_Q$	configuration (structural) and inertial entropy
u_e	the density of the potential (hidden) component of internal energy in deformable volumes
$\vec{q}$	specific energy of dynamic heat transfer (dissipation)
μ_{elast}, μ_{plast}	elastic and plastic friction coefficients
W	probability of a compatible tribosystem state
k	Boltzmann constant
ΔH_S	enthalpy of melting
*	critical values of process parameters

FUNDING

The work was supported by ongoing institutional funding. No additional grants to carry out or direct this particular research were obtained.

CONFLICT OF INTEREST

The authors of this work declare that they have no conflicts of interest.

REFERENCES

1. Kragel'skii, I.V., *On friction of unlubricated surfaces, Vsesoyuznaya konferentsiya po treniyu i iznosu v mashinakh (All-Union Conf. on Friction and Wear in Machines)*, Moscow: Izd-vo Akad. Nauk, 1939, vol. 1.
2. *Poverkhnostnaya prochnost' materialov pri trenii* (Surface Strength of Materials under Friction), Kostetskii, B.I., Ed., Kiev: Tekhnika, 1976.
3. Fedorov, S., Selforganized nano-quantum solid lubricant, *Tribologie + Schmierungstechnik*, 2016, vol. 63, no. 3, pp. 5–13. https://elibrary.utb.de/doi/abs/10.5555/tus201630005.
4. Fedorov, S.V., *Osnovy triboergodinamiki i fiziko-khimicheskie predposylki teorii sovmestimosti* (Fundamentals of Triboergodynamics and Physical and Chemical Prerequisites of Compatibility Theory), Kaliningrad: Kaliningrad Gos. Tekh. Univ., 2003.
5. Lakhtin, Yu.M. and Leont'eva, V.P., *Materialovedenie. Uchebnik dlya vysshikh tekhnicheskikh uchebnykh zavedenii* (Materials Science: Textbook for Higher Technical Institutions), Moscow: Mashinostroenie, 1990, 3rd ed.
6. Grabskii, M.V., *Strukturnaya sverkhplastichnost' metallov* (Structural Superplasticity of Metals), Moscow: Metallurgiya, 1975.
7. Bridgman, P.W., *Studies in Large Plastic Flow and Fracture: With Special Emphasis on the Effects of Hydrostatic Pressure*, New York: McGraw-Hill, 1952.
8. Ludwik, P., *Elemente der Technologischen Mechanik*, Berlin: Springer, 1909. https://doi.org/10.1007/978-3-662-40293-1
9. Zener, C. and Hollomon, J.H., Problems in non-elastic deformation of metals, *J. Appl. Phys.*, 1946, vol. 17, no. 2, pp. 69–82. https://doi.org/10.1063/1.1707696
10. Fedorov, V.V., Ergodynamic concept of failure. 1. Basic statements of the ergodynamics of deformed bodies. Criteria of failure ductility, *Strength materials*, 1991, vol. 23, no. 8, pp. 883–889. https://doi.org/10.1007/BF00772491
11. Vladimirov, V.N. and Romanov, A.E., *Disklinatsii v kristallakh* (Disclinations in Crystals), Leningrad: Nauka, 1986.
12. Panin, V.E., Physical mesomechanics of surface layers in solids, *Fiz. Mezomekhanika*, 1999, vol. 2, no. 6, pp. 5–23.