Hamilton's Principle and Energy Profitability

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Abstract— *The kinetics of the interface between metals under contact and external influences (triboloading, rolling, physical and chemical effects of the environment, etc.) has been investigated. It is shown that the kinetics of the evolution of the structure of materials proceeds in accordance with the minimum production of entropy and maximum destruction. The conditions for obtaining a special nonequilibrium state of the crystal lattice of nickel under triboloading are determined. The main regularities of the kinetics of structural transformations, structural-scale levels of deformation and the properties of the interface between metals during contact and external interaction have been determined.*

Keywords— principle of least action, energy profitability, nanocrystalline and submicrocrystalline structures invariants; dislocations, stresses, laws of kinetics, entropy, destruction.

I. INTRODUCTION

The accumulated experimental database in the field of research of metal interface kinetics does not allow to use it to the full extent to create a database, for example, on tribotechnical characteristics and wear. The experimental data given in different sources differ from each other. On the one hand, this can be explained by some differences in the modes and technologies of obtaining the surface, as well as the conditions of their testing, and on the other hand by the lack of scientifically sound fundamental principles and, as a consequence, measurement parameters. The fragmentation of fundamental research directions and purely practical approach to solve applied and immediate problems, unfortunately, does not allow to concentrate efforts on classification and systematization of data in the fields of metallophysics, tribochemistry, condensed state physics and nanomaterial science. The obtained results of plastic deformation studies are often controversial and sometimes contradictory. The current state of the problem of studying the surface kinetics of metals and the creation, including nanomaterials is characterized as a transitional period between the accumulation of experimental data and their interpretation in the categories of mechanics, physics, chemistry and the development of generalizing invariants and regularities that do not depend on the modes, conditions and technologies of their production [1, 2].

The lack of a systematic approach leads to the fact that the problem of contact interaction of surfaces of different materials in terms of optimal selection to improve their wear resistance has not yet been solved. Experimenters, unfortunately, do not take into account the large-scale factor of external influence, for example, load-velocity parameters on the surface of materials. Obtaining a momentary and quick "positive" result of research puts the experimenter in the limited conditions of hard, not soft impact on the material. As a result, as a rule, many processes (heat conduction, diffusion, mass transfer, hardening, amorphization, fracture, etc.) occur simultaneously and we cannot divide a complex process into composite and simpler ones. It is this systematic and thorough approach that allows researchers to divide a complex process into simple processes and establish the course of the dominant process in their diversity and, as a consequence, to identify and establish the main fundamental regularities describing this simple process. The level of understanding of the problem by the author of this article is fully consistent with the works and statements of R. Feyman, V.D. Kuznetsov and I.V. Kragelsky [3–5] and others. The most common fatigue [6], energy [7] and lobe [8] theories do not consider the kinetics of layer-by-layer hardening and fracture of the surface layer of metals in detail, taking into account all (nano, micro, meso and macro) structural and scale levels of deformation. The mechanisms of fragmentation and relaxation channels of strain energy accumulated in the surface layers of conjugated materials are not fully understood. The process of superplasticity has not been fully investigated in which the

conditions of amorphization of the surface layer and facilitated slip of submicro and nanostructured elements relative to each other will be realized in the absence of hardening. Understanding of the short-range interaction between inter-nodal atoms and the electronic subsystem in the formation of nonequilibrium states of nanoclusters and their conglomerates will make it possible to realize corporate phenomena in nanomaterials to reduce their brittleness and increase their operational properties [9, 10].

Another reason for not studying this issue is the lack of fundamental approaches and scientific ideas for the study of strongly nonequilibrium thermodynamic systems. In the case of a nonequilibrium state of a surface in the accumulation of its strain energy using various model representations, the problem of interpreting the results of quantitative assessment of the magnitude of stresses and dislocation density arises [11].

Plastic deformation of solids is realized at several interrelated structural levels, the scale of which is determined by the physical nature of structural defects responsible for the shape change [12]. In most cases, the distribution of localization zones is ordered in space and time, and the type of localization is determined by the law of plastic flow. Consideration of a solid body as a multilevel hierarchically organized system consisting of 3D-crystalline and 2D-planar subsystems causes a sharp increase in the role of the curvature of the crystal structure in describing the behavior of solids in the fields of external contact effects [13, 14].

The purpose of the work is to determine the physical essence of the principle of least action and energy benefit to describe physical systems under external actions.

II. EXPERIMENTAL DETAILS

The effectiveness of studies of physical regularities of plastic deformation, hardening and fracture of surface layers of solid bodies under their frictional loading is largely determined by the level of experimental research due to the correctness of the applied methods, correctness and sufficient sensitivity of the applied research methods. In order to solve the problem of hardening and fracture of metal surface layers under frictional loading, it was necessary to use a wide range of modern physical research methods, such as ferromagnetic resonance, transmission electron microscopy, X-ray diffraction and metallographic analysis, medium and low energy electronography, etc. [15]. In accordance with the specifics of the tasks to be solved and the properties of the investigated objects, in some cases it was necessary to create specialized equipment [15]. In this regard, a technique for estimating the dislocation density was developed and the ferromagnetic resonance apparatus was created [15]. For electron-microscopic studies of the structure on the “lumen”, the methods were improved and the tribometer units of specimen testing and unilateral electrolytic thinning were created [15].

Nuclear magnetic resonance (NMR) and electron paramagnetic resonance (EPR) methods have been widely used to study the wear kinetics of surface layers under triboloading [16]. The complex of these methods, along with transmission electron microscopy, allowed us to establish the relationship between the microstructure of the surface layers of solids and changes in the lubricating medium and wear kinetics.

The priority elements of this study are also the techniques of specimen preparation, their friction testing and a comprehensive study by the above mentioned methods. The disks of $\approx$ 5x0.5 mm^2 were cut from 99.99% purity nickel foil produced by electron-beam melting using the electrospark method. Before friction testing, the specimens were electrolytically polished and annealed in a vacuum of 0.133 mPa at 973 K. The friction test was carried out on a machine of type AE-5 with a precision setting of the contact plane [15]. Triboloading of sliding Ni-Mo pair was carried out mainly in TsIATIM-201 grease at nominal contact pressure $\approx$ 84 and $\approx$ 168 kPa and linear velocity $\approx$ 0.5 m/s.

Experimental FMR methods are the most convenient in the study of the dislocation structure of ferromagnetics, because at the frequency of the external electromagnetic field ν = 9600 MHz, the broadening of the resonance absorption line in a deformed ferromagnet is caused by the elastic fields of dislocations, while small-scale defects (vacancies, embedded atoms) and large-scale defects (cracks, pores, etc.) drop out of the absorption spectrum [15]. In these works, the dependence between the width of the FMR line (Δ H) and the dislocation density (ρ) was established. In the strain range $\varepsilon \approx 0$ - 75 % there is a linear dependence between the line broadening and dislocation density. At large deformations, the broadening of the FMR line is described by an inverse root dependence. The absence of line broadening in a deformed ferromagnet with a magnetostriction

constant equal to zero (permalloy) confirms the physical meaning of ΔH broadening due to local magnetic fields around dislocations [17, 18].

Another advantage of this method is that at this frequency, the penetration depth (δ) of the ultra-high frequency (UHF) field in metallic materials is $\delta = 10^{-7}$ to 10^{-6} m. This determines the selectivity of the method for the informativeness of the defective microstructure of thin surface layers, especially under frictional loading, when plastic deformation covers these layers commensurate with the skin layer thickness [19]. In accordance with the above provisions of FMR, direct electron microscopic and X-ray diffraction studies of thin surface layers of steel [20], the observed cyclic dependence ΔH = f(t) reflects the kinetics of the dislocation structure of the surface layer of a frictionally loaded ferromagnetic.

Electron-microscopic studies of nickel were carried out on an EVM-100AK microscope using the thin foil method "per lumen" and HITACHI H-800. The dislocation density data were obtained by averaging, while viewing, at least five localized sites in different grains.

It should be noted that triboloading is a small-amplitude, alternating (compression and tension of near-surface volumes) and cyclic contact loading of metal surfaces [21-23], where hardening and fracture can only be represented from dislocation representations [24].

III. RESULTS AND DISCUSSION

3.1 Using the principle of least action (PLA) to describe physical systems:

It is known that PLA or Hamilton's principle principle is used to formulate the equations of motion of a material point in mechanics [25]. Why this fundamental principle cannot be used to describe the kinetics of the processes of structural transformations in materials occurring in the same continuum of space and time? The question naturally arises, namely: where there is symmetry, there should be invariants to describe the kinetics of various structural transformations in multilevel, hierarchically organized processes occurring on the surface of metals? The kinetics of the system transition from one structural state (A) to another (B) is carried out in accordance with the PLA describing all structural-scale levels of deformation (Fig. 1).

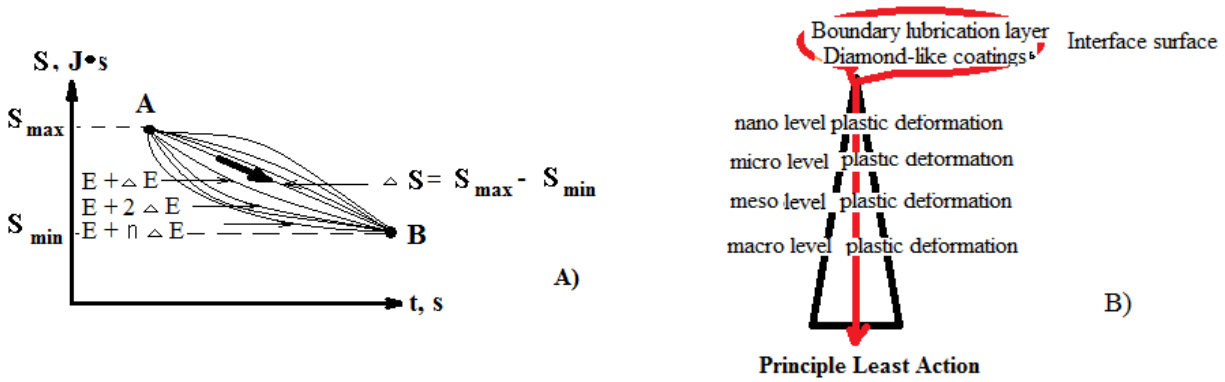


FIGURE 1: Principle Least Action (PLA): a) kinetics of system transition from one structural state (A) to another (B) according to LAP, where S – action, t – time; b) PLA action scheme covering all structural-scale levels of deformation

It is known that the mathematical formulation of the PLA for the motion of a material point is [25]:

$$\delta S = 0 , \tag{1}$$

Where

$$S = \int_{t_1}^{t_2} L(q, q', t)dt \tag{2}$$

where q, q/ – independent parameters characterizing the system, t – time. The integral in expression (2) takes the minimum value along the straight line AB (Fig. 1, A) and the expression is valid:

$$\delta S = \int_{t_1}^{t_2} \left(\frac{\partial L}{\partial q}\delta q + \frac{\partial L}{\partial q'}\delta q'\right)dt = 0 \quad (3)$$

Where the Lagrangian is given by the expression [25]:

$$L = E_{kin} - U_{poten} \quad (4)$$

Where E_{kin} – is the kinetic energy and U_{poten} – is the potential energy of the material point under the given external influence.

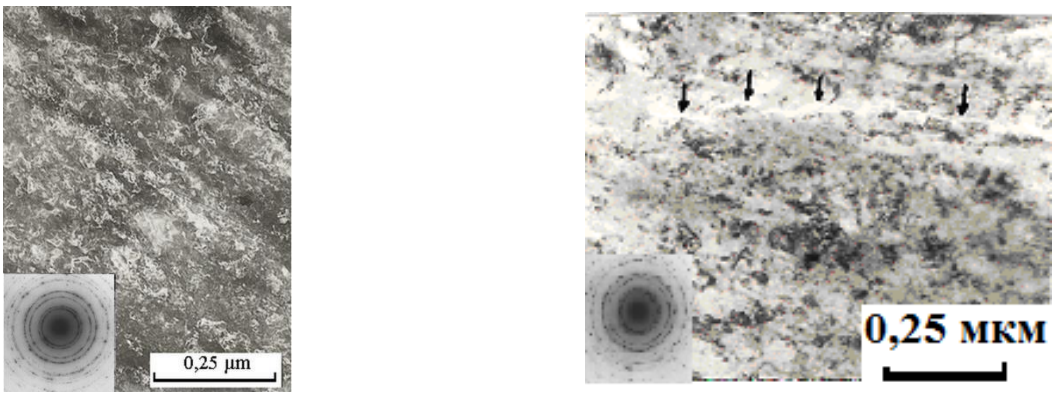
Under the action of external influences, ions in the nodes of the crystal lattice of metals or a set of ions forming the nucleus of a linear defect-dislocation or a set of dislocations in the form of boundaries (NC) or SMC structures move in elastic stress fields. In mechanics, the equation of motion of a material point is described by Newton's second law or using the principle of least action (PLA). The PLA was used to determine the frequency of oscillations of crystal sublattices ($\approx 4.87 \cdot 10^{13}$ s^{-1}) of positive and negative ions in two atomic crystals of NaCl or CsCl under external influences [26]. Besides, the Lagrangian formalism was used to describe physical systems under friction in [27]. However, there is no idea of justification of search and establishment of invariants in these works.

The penetration of light from one medium into another is described by Fermat's principle or the principle of least time or, respectively, integration along the path of least time leads to the realization of the principle of least action of PLA [3]. The equation for the self-consistent electromagnetic field and interacting photons is given in [28].

3.2 Using the principle of energy profitability (EP) to describe physical systems:

According to the second law of thermodynamics, an open physical system tends to a state characterized by the minimum of energy that is accumulated in it under external influences (it is impossible to transfer heat from a colder body to a hotter one) [29]. Therefore, the physical system seeks channels of energy relaxation. Naturally, the system finds the path that requires the minimum value of energy expenditure or the minimum work done [30, 31]. We give specific examples from the kinetics of nickel structure evolution under triboloading or rolling, which are in full agreement with the results given in [32–34].

Pre-annealed nickel samples subjected to triboloading already at the beginning of the process at 0.9 kc form NC states in the form of closed dislocation loops or twins. Under non-equilibrium deformation conditions, it is energetically advantageous (minimum of work done) for the material to form NC states (Fig. 2), since the number of moles in this case increases by two or three orders of magnitude and, accordingly, the energy dissipation area increases. The latter forms a relaxation channel for the energy accumulated during triboloading.



(A) **(B)**

FIGURE 2: Formation of nanostructures at t = 0.9 ks on the nickel surface at nominal contact pressure: a) 84 kPa; b) 168 kPa

The slip band blocked by the grain boundary can be simplistically represented as a curved segment of fixed length L (grain size ≈ 30 μm) (Fig. 3, a) with a certain curvature λ (Fig. 3, b).

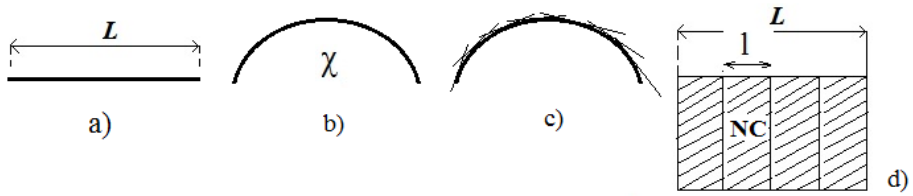
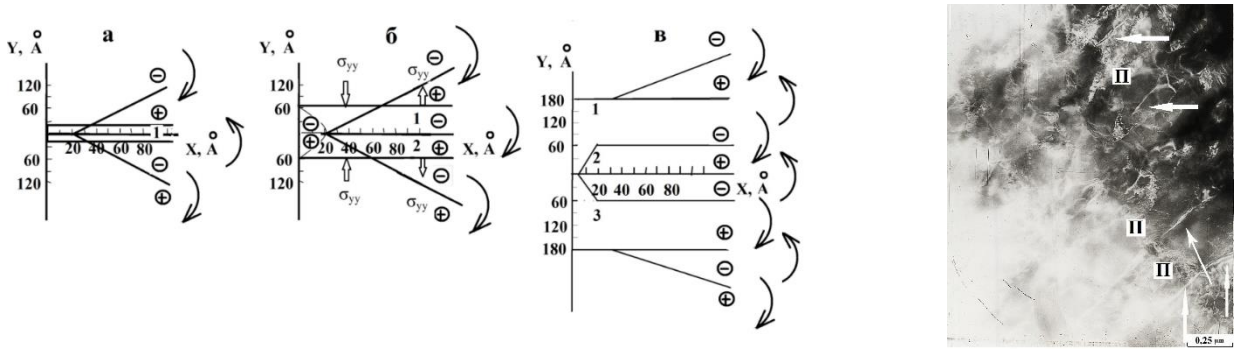


FIGURE 3: The scheme of SMC and NC states formation: a) initial structure in the form of a segment; b) structure evolution in the form of a segment bending under the action of external influences; c) beginning of SMC and NC states; d) formed SMC and NC states

Energy relaxation is realized by shifting and rotating the corresponding segments that make up the segment (Fig. 3, c), i.e., it is energetically favorable for it to break into segments (rectilinear sections) with zero or minimum possible (tending to zero) local curvature (Fig. 3, d). Energy relaxation is realized by shifting and rotating the corresponding segments that make up the segment (Fig. 3, c), i.e., it is energetically favorable for it to break into segments (rectilinear sections) with zero or minimum possible (tending to zero) local curvature (Fig. 3, d). The energy of the system in this case tends to the minimum value.

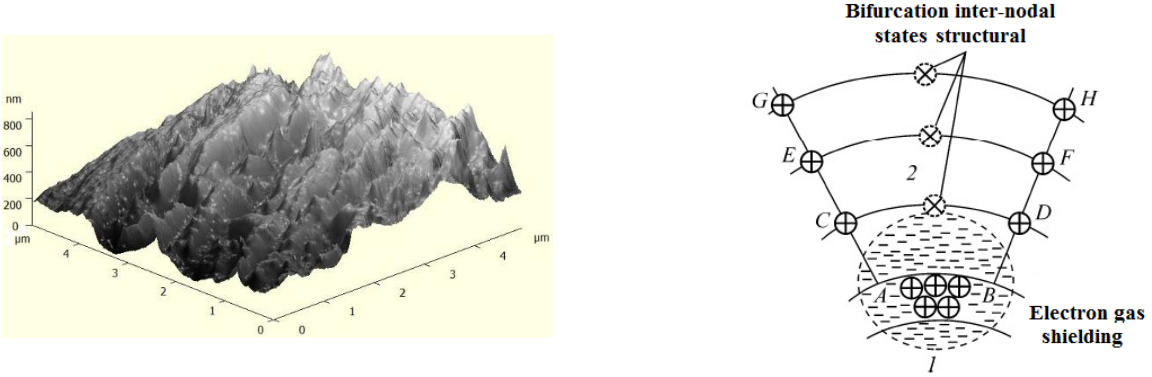
The most striking example of EP is the formation of slip bands, where a minimum of energy input is required to slide volumes of material relative to each other. Grain-boundary sliding of one grain in relation to neighboring grains, rather than grain-boundary sliding of a set of grains (10 or 100 grains) to a set of neighboring grains. In both the first and the second case, the sum of stress moments is zero and the condition of material continuity is fulfilled. However, in nature the first case is realized, i.e. the physical system chooses the path that requires minimum cost or work.



(A) **(B)**

FIGURE 4: A) grain boundary slip pattern and distribution of compressive and tensile stresses, where minus the compression region, plus the stretching region; B) slip bands (arrows show microcracks along the slip bands)

The complex stress state of the compression and tension regions determines the formation of a developed relief with a folded structure on the nickel surface under triboloading (Fig. 5, a). The latter is possible only by forming a crystal lattice in the tensile regions with high local curvature (Fig. 5, b).



(A) **(B)**

FIGURE 5: A) AFM image; B) bifurcation inter-nodal structural states in the zone of local curvature of the crystal lattice, where AB are clusters of positive ions at the boundary of grains 1 and 2 (B)

Similarly, the aggregation of micropores and microcracks into pores and cracks at grain boundaries (intergranular fracture) and (transgranular fracture that passes through the grain) proceeds in accordance with EB (Fig. 6).

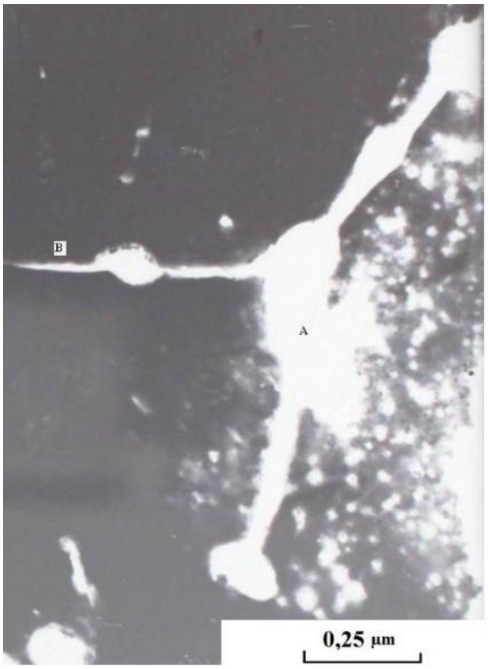
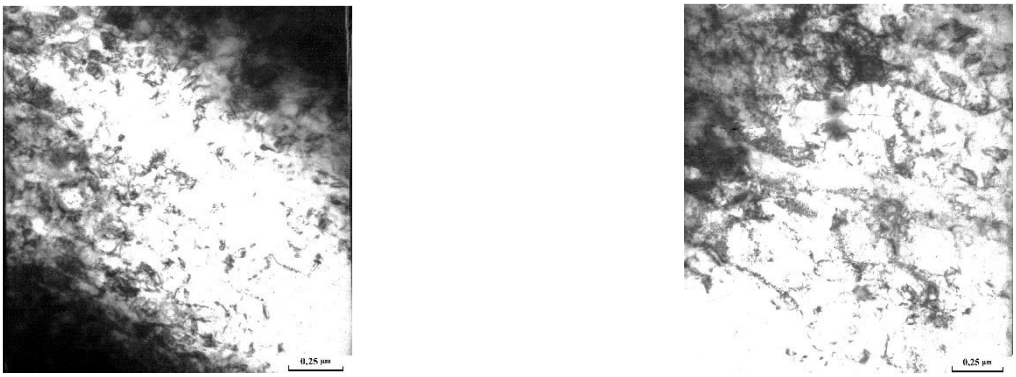


FIGURE 6: Inter- and transcrystalline fracture

Energy accumulation in the subsurface layers of nickel causes transverse sliding of dislocations in strips and their fragmentation. A submicrocrystalline structure (SMC) is formed with the time of frictional loading. The increase in image contrast confirms the accumulation of energy by the nickel surface with the triboloading time (Fig. 7).



(A) **(B)**

FIGURE 7: SEM images of SMC structures formed on the nickel surface with triboloading time: A) SMC structure (t = 52 ks); B) SMC structure (t = 75 ks)

The same principle of EB describes the model of lobe fracture, where the separation of the lobe is energetically advantageous and prevents the development of cracks deep into the metal. Changing the direction of the dislocation flow outward rather than inward and the onset of an avalanche-like selective mechanism of destruction of a metal layer hundreds of microns thick is also EP. The formation and motion of domain boundaries in paramagnetics, magnetic properties of paramagnetics and ferromagnetics (Larmor's theorem) in an external magnetic field are described on the basis of EP [16]. The flux of energy or work done in time to overcome the Peierls-Nabarro forces when dislocations move is also the smallest in densely packed directions. Therefore, the direction of dislocation motion coincides with the densest packing of atoms in the nodes of the crystal lattice [30].

The increase of dislocation density up to 10^{18} m^{-2} determines high catalytic activity of the surface. The latter causes a decrease in the free surface energy by transition from physical adsorption to chemisorption of the boundary lubricating layer (BLL) molecules with the metal surface (Fig. 8).

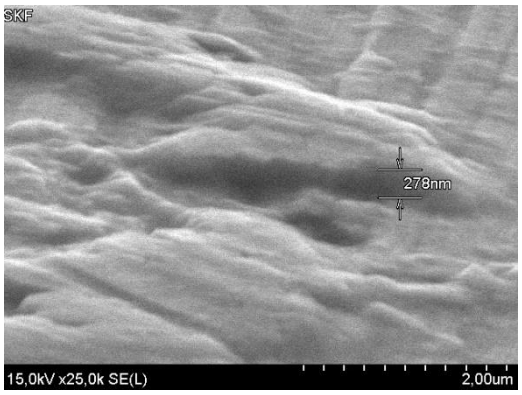


FIGURE 8: Electron microscopic image of 6202-2RS d16 C3 bearing ring surface with a chemisorbed LGBH-2 grease layer formed on it

Thus, the whole kinetics of structure formation at different scale levels, its evolution and destruction proceeds in accordance with energy profitability (Fig. 9).

The strength properties of BLL increase and the elastic modulus of such layers is ≈1.4 GPa, which is comparable to the elastic modulus of rubber.

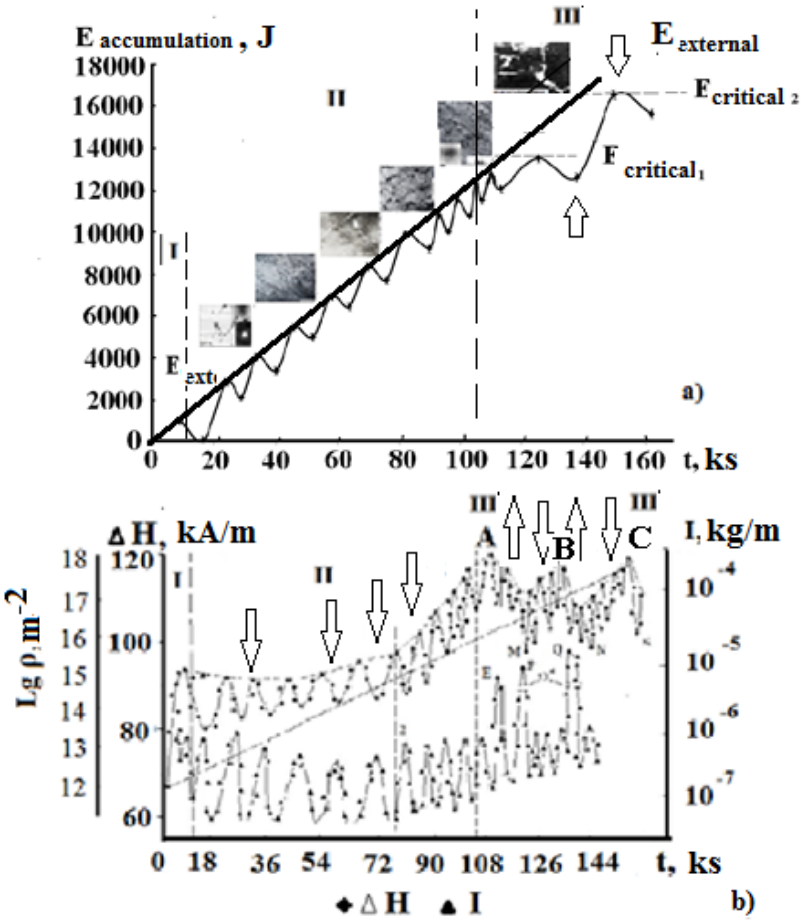


FIGURE 9: Dependence of kinetics of structural changes in the surface layer of nickel under triboloading: (a) - dependence of the external impact energy ($E_{external}$) of the accumulated energy (E_{ac}) on time (t), where $E_{critical\ 1}$ and $E_{critical\ 2}$ are the values of the critical energy for the destruction of the meso- and macroscale level of deformation; (b) - dependence of the broadening of the ferromagnetic resonance line (ΔH), dislocation density (ρ), wear intensity (I) on time (t) of triboloading

The number and size of defects determine the process of their interaction (Fig. 9, region III). An increase in the dislocation density up to some critical value $\rho \approx 10^{18}$ m^{-2} determines the convergence of dislocations to a distance of ≈ 50 nm and causes the overlap of the elastic fields of linear defects [15], which leads to a change in the direction of dislocation flows outward (Fig. 9, b). The surface is prepared for selective fracture mechanism [15]. This effect, the change of the dislocation flow direction under external influences, can be used for the development of sensors.

Consider the equilibrium deformation region (Fig. 9, region II). In Fig. 9, a, the curve $E_{ac}(t)$ has a monotonically increasing and oscillating dependence in time. Each cycle of change in the value of stored energy $E_{ac}(t)$ corresponds to a cycle of change in strength characteristics $\rho(t)$ and change in wear intensity I(t) (Fig. 9, b, region II). The latter is determined by the physics of the process of accumulation of dislocation density (clumping), their facilitated exit to the surface (Rebinder effect [35, 36]) with the formation of nanocrystalline (NC) structures on the surface under triboloading in accordance with the scheme shown in Fig. 10. The increase in dislocation density proceeds up to some critical value, and then a lobe fracture mechanism occurs, accompanied by a decrease in dislocation density. The variation of free energy (E_{free}) and wear (I) from time t at constant contact pressure is presented. The plateau in Fig. 10 corresponds to the formation of a stable dissipative structure. The increase in dislocation density proceeds up to some critical value, and then a lobe fracture mechanism occurs, accompanied by a decrease in dislocation density. The variation of free energy (E_{free}) and wear (I) from time t at constant contact pressure is presented. The plateau in Fig. 10 corresponds to the formation of a stable dissipative structure.

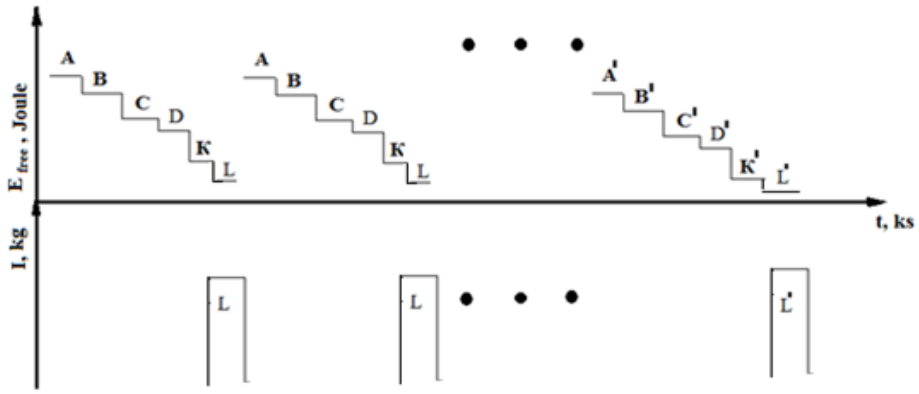
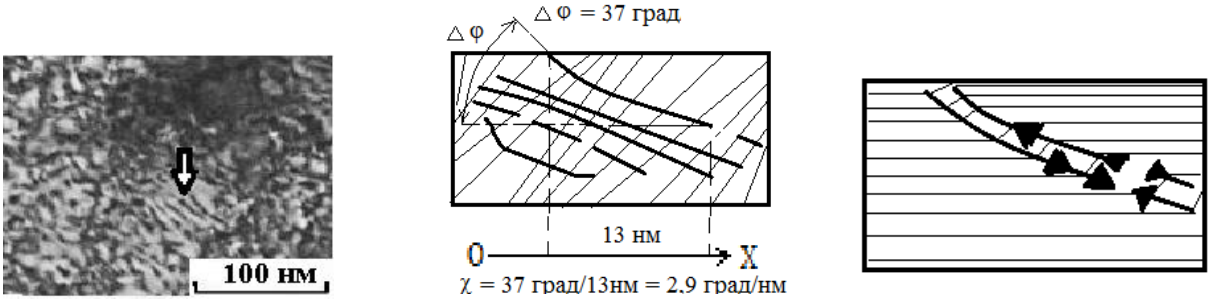


FIGURE 10: The generalized scheme of the kinetics of the free energy (E_{free}) and wear (I) changes of the metal surface layer for the equilibrium deformation region of the surface layer of metal. The structural formations: A - corresponds to nano- and submicrostructure; B - cellular or lamellar structure; C - slip bands; D - micropores; K - structure corresponding to transcrystalline and intercrystalline fracture of metal surface; L - structure corresponding to juvenile metal surface

Each formed dissipative structure will correspond to its own energy pumped into the system (ΔE_{free}). Each cycle of hardening and destruction of the surface layer (Fig. 9) corresponds to its structural changes A-K. The following structural formations are formed on the nickel surface under friction over time: A - corresponds to nano- and submicrostructure; B - cellular or lamellar structure; C - slip bands; D - micropores; K - structure corresponding to transcrystalline and intercrystalline destruction of the metal surface (Fig. 6); L - structure corresponding to juvenile metal surface. The latter is confirmed by analyzing the dislocation density on electron microscopic images of the nickel surface obtained at different times and corresponding to the wear intensity maxima [15]. The phenomenological model of lobe-layer fracture of the nickel surface layer under triboloading is described in [15].

Let us consider the region of nonequilibrium deformation (Fig. 9, b, region III). The amplitude of FMR line broadening (ΔN) for one cycle of change in strength characteristics of the nickel surface layer under triboloading is at least three times smaller than the amplitude of FMR line broadening (ΔN) for one cycle of change in strength characteristics in the region of equilibrium deformation (Fig. 9, b, region II). Since energy is directly proportional to the square of the amplitude, in the region of non-equilibrium deformation, the physical system reduces by an order of magnitude the energy cost between the upper and lower amplitude point of the hardening-strengthening cycle. With increasing strain energy accumulated in the nickel surface layer, the level of strain relaxation activation energy decreases so much that it acts as a regulator of both the number and size of defects and the way of their distribution and corporate interaction in accordance with the principle of energy profitability.

The formation of nanodoubles and nanodipoles of partial disclinations as carriers of noncrystallographic shift (Fig. 11, a, arrow, b and c), is also energetically advantageous, since the elastic field of interaction is localized between the elements of these structures rather than outside them, which determines a decrease in the value of the stored energy in the crystal lattice [34].



(A) **(B)** **(C)**

FIGURE 11: A) Propagation of nonlinear plastic distortion waves on nickel surface (t = 133 ks), B) schematic representation of nanobands (plastic distortion waves), C) schematic representation of nanobands as a set of partial disclinations

For materials made of copper, aluminum, nickel, etc., obtained by equal-channel angular pressing and severe plastic deformation on Bridgman anvils, for the curvature of the crystal structure, values of tens of deg/μm are characteristic, and for NC materials - hundreds of deg/μm [37–39]. The latter is fulfilled at high values of internal stresses, usually an order of magnitude lower than the elastic modulus of the materials. In our case, at long-term (t > 108 ks) triboloading of the nickel surface layer $\chi \approx 1$ deg/nm, i.e., at least an order of magnitude higher. These results indicate an intensive fragmentation of the crystal lattice of the nickel surface layer under triboloading in the environment of surface-active substances, which promote an intensive exit of dislocations to the surface under the action of image forces and their splitting.

The fulfillment of the energy balance under triboloading will have the form [2]:

$$E_{exter} - E_{ac} = H + M, \tag{5}$$

Where H – is the entropy given by expression (5), M – is the energy determined by the mass of wear particles. Then it is obvious that the formation of NC and SMC structure at the points of contact of curves E_{exter} and E_{ac} is accompanied by entropy decrease (Fig. 9, a), since the area between these curves tends to zero. Table 1 summarizes the specific values of entropy and energy estimation, determined by the mass of worn particles, in the formation of a particular structure in the surface layer of nickel under triboloading. In the region of strongly nonequilibrium deformation, the formation of NC structures will also be accompanied by a decrease in entropy (Fig. 9, a, region III), but not as significant as for the region of equilibrium deformation (Fig. 9, a, region II). The entropy values in region III take both maximum and minimum values (Fig. 9, a, region III, arrows) at specific time values, which is consistent with the works [40, 41]. The entropy values in region III take both maximum and minimum values (Fig. 9, a, region III, arrows) at specific time values, which is consistent with the works [40, 41]. However, the entropy flux in time according to the principle of EP and PLA should take a minimum value. That is, the expression is fulfilled:

$$\int_{t_0}^{t_1} (E_{exter} - E_{ac})dt = \int_{t_0}^{t_1} (H + M)dt \tag{6}$$

or taking into account the expression for entropy [42]:

$$H = \frac{\zeta(\nabla \mathrm{T})^2}{\mathrm{T}^2} + \rho\frac{\mathrm{Z}\Sigma}{\mathrm{T}} \pm \frac{\rho}{T^2}([\alpha,\Omega],\nabla T,t) \tag{7}$$

Where ς - thermal conductivity, ρ - material density, Z - defect flux density, Σ - hydrostatic stress in the defect phase formation zone, parameters α and Ω characterize the energy flux through the surface. The first summand in expression (7) describes entropy production associated with heat generation. The second summand in expression (7) determines the work of the defects flux when they move in the stress field. The third summand in expression (7) describes the energy flow of the crystal mechanical field through the surface [42].

Thus, the value of the time integral in expression (8) takes the minimum value.

$$\int_{t_o}^{t_1}(H+M)dt=\int_{t_o}^{t_1}(\zeta\frac{(\nabla T)^2}{T^2}+\rho\frac{Z\sum}{T}\pm\frac{\rho([\alpha,\Omega],\nabla T,t)}{T^2}+M)dt \quad (8)$$

A truly physical system finds paths that require the least amount of work. Let us give some examples. In the region of equilibrium deformation (Fig. 9, region II), the time period of one cycle of hardening and de-hardening (≈18 ks) accompanied by flake fracture of a thin layer is 8 times longer than in the region of non-equilibrium deformation (≈2.3 ks) (Fig. 9, region III). Thus, in accordance with the PLA, the value of the work done per one hardening - de-hardening cycle decreases. At points A, B and C (Fig. 9, b) the dislocation density values reach maximum values, which corresponds to surface hardening and formation of NC states after these points selective fracture mechanism with exposure of juvenile surface occurs. However, the time interval between the onset of the selective fracture mechanism is: OA (from the moment of the beginning of triboloading) is ≈ 108 ks; AB is ≈ 34.105 ks, and between points BC is ≈ 20.845 ks. That is, the work or action done by the friction force at each subsequent time interval is less than at the previous one. The physical system has realized the path in accordance with the PLA and EP, at which the minimum work for the realization of the selective destruction mechanism is performed. The physical system finds a path of energy relaxation in accordance with the PLA, at which the minimum work is done to realize the selective destruction mechanism. The question of mathematical formulation of the external impact on the physical system is open and debatable. The value of the integral over time in expression (8) takes the minimum value (table 1), based on the fulfillment of the energy balance (6).

TABLE 1
QUANTIFICATION OF ENTROPY AND ENERGY, DETERMINED BY THE MASS OF WORN PARTICLES, IN THE FORMATION OF A PARTICULAR STRUCTURE IN THE SURFACE LAYER OF NICKEL UNDER TRIBOLOADING

Type of structure	t, 10^3 s	H+M, entropy plus energy determined by the mass of wear particles, 10^6 J·s
NC structures	0.9	0.097200
Slip strips	6.5	2.514270
Fragmented NC and SMC structures	108	57.828210
Loose and porous surface layer	160	120.380200

Execution of the energy balance (5) taking into account the expression for the dislocation energy shows that in the conditions of strongly nonequilibrium system (Fig. 9, region III), the number of point defects (atom-vacancy states) increases by orders of magnitude (3-5), i.e. their role sharply increases in the description of such systems.

Thus, the ways to describe the external influence on a system (physical, chemical, biological [2]) can be different: the principle of least action or energy profitability, but the result is the same (Fig. 12).

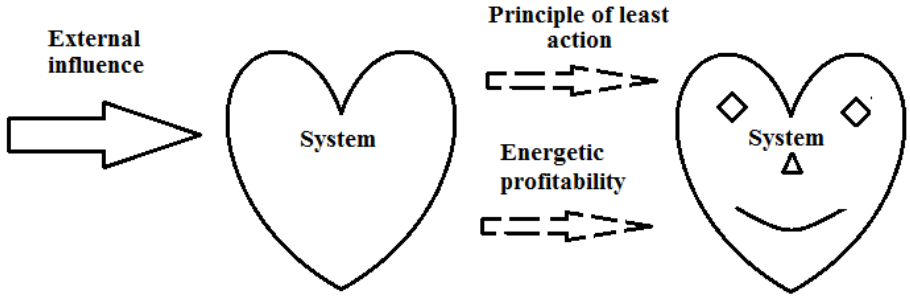


FIGURE 12: The scheme of external influence on the system (physical, chemical, biological) and its description by the method of energetic profitability and the principle of least action

It is established that the kinetics of the structure formation and evolution of the metal interface surface under external influences proceeds in accordance with the following provisions of thermodynamics:

- To each steady state of the metal interface will correspond its own structure with a certain value of free energy and, accordingly, with types of its redistribution between the elements of the boundaries and within the structural formation;

- If the action of load-velocity parameters or external influence exceeds some critical value of the energy supplied to the system, then it passes to a new structural state in accordance with EP and PLA and characterized by a lower value of free energy;
- The intensity of external impact determines the duration of the cycle of change in strength characteristics, the amount of strain energy accumulation and the degree of fragmentation of the surface layer of metals and, accordingly, the gradient of disorientation between structural elements, where the number, density, and their interaction (nano-, submicro-, slip bands, pores, etc.) determine the dominant role of one or another scale level of plastic deformation at a given moment of time of the kinetics of structure formation and the mechanism of its destruction in accordance with EP and PLA.

IV. CONCLUSION

The physical essence of the processes: heat conduction, diffusion, mass transfer, hardening, amorphization, fracture, etc., occurring at contact localized interaction of metal surfaces, and the result is the same and does not depend on the way of its description. The work done or the response of a physical system (material) is commensurate with the magnitude of the external influence. It does not matter what mathematical approach we use (calculus of variations to describe IPA or differential equations based on Newton's laws, continuum physics, kinetics of physical and chemical processes) to describe physical processes in a solid body.

The main thing is the result in the form of minimum energy costs for the formation, evolution and destruction of a structure with certain properties. However, the PLA (Hamilton's principle) is a more basic and fundamental principle, as it describes equilibrium and non-equilibrium processes than the minimum or maximum of entropy production for describing non-equilibrium processes. In addition, the use of PLA implies, based on the properties of space and time symmetry, the search and establishment of invariants, which does not follow from the principle of energetic favorability. The latter is most important as it has practical value in the study and evolution of the properties of emerging structures. Analysis of literature data and the existence of invariants, for example, in chemistry (D.I. Mendeleev's table, the law of conservation of mass during chemical reactions), biology (Mendel's second law), nuclear and quantum physics (conservation laws, etc.) determine the fundamentality and universality of the use of PLA and energy benefits for processes occurring in the space-time continuum. The issue of the inverse effect of material properties on the properties of the space-time continuum is debatable and open to further research.

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