Determination of the physical parameters of the hardness and strength of the material, according to the force diagram of nano-micro indentation.

Shtyrov Nikolay *

Private Research and production Company "LYU". Nikolayev, *Ukraine, 54020, PO Box 86, Ukraine , +380675102044*, Director Shtyrov Nikolay * E-mail: nasht@ukr.net

Highlights. A deformable solid is presented as a physical macroscopic thermomechanical rheological system formed by waves - quasiparticles. The dependences and universal physical parameters of the strength of materials are theoretically substantiated; on their basis, an algorithm and computer method for calculating the standard mechanical indicators are developed: proportionality limit, ultimate strength, fatigue, etc. Methods for analytical assessment of universal physical parameters of material strength (boundary conditions of the equation).The method is based on physical analysis of the results of standard tensile tests to fracture ISO6892-84, analysis of kinetic indentation data ISO 14577-1: 2002.

Abstract

The results of an analytical study of the standard force kinetic diagram of indentation by methods of the physical structural-energy theory of solid strength are presented. Methods for determining the universal physical kinetic macro, nano-micro hardness of a material. Physical model of the process of irreversible energy transformations of the nano-microstructure of the material. Equation and structural-physical parameter of the nano-micro hardness of the kinetic indentation of the material. Analytical methods for calculating strength, durability, damage, plasticity of a material using universal structural and energy molar physical parameters. The relationship between the molar strength parameter and the structural-physical parameter of the nano-micro hardness of the material. Prospects for the application of the physical method for the analysis of nano-micro indentation and the structural-energy theory of strength.

Key words: theory, calculation methods, physical parameters of strength, durability, hardness, indentation.

Objective.

Acquaintance with theses of the physical structural-energy theory of strength. An example of calculating the parameters of strength, durability, damage, using the molar physical parameters of the material. The results of the analytical analysis of the force diagram of macro and nano-micro kinetic indentation of the material by the methods of physical theory. The empirical and physical hardness of the material. Structural-physical parameter of a material in the equation of nano-micro hardness, properties. The ratio of the physical hardness parameter of nano-micro indentation and the structural-energy molar parameter of the strength and durability of the material. Prospects for the application and development of the physical approach.

1. Physical theory of strength.

In the physical structural-energy theory of strength (hereinafter briefly SET) [1,2,3,4] a deformed solid (DS - deform solids) is considered as a physical medium, a macroscopic system, which is characterized by mechanical, thermodynamic and statistical particle-wave properties and parameters: molar energy, molar thermodynamic potential, molar volume, etc. Let's consider the basic concepts of the theory.

Molar energy $W_L, J/mol$ is a physical characteristic of a macroscopic set of elementary states of far and near corpuscular-wave interaction of structural units that form a volume DS of different nature, in the presence of a stress field and temperature. The elementary state of molar energy is considered as a corpuscular-wave process of CE interaction, which occurs in a small volume of the quasi-equilibrium system DS. The interaction process is a continuous movement and transformation of nano-micro CW energy flows between elementary small volumes of DS. In each elementary molar volume, there is a continuous oscillatory process, conversion of kinetic CW energy into potential CW energy, etc. An elementary physical measure of the energy of a quasi-equilibrium volumetric process (elementary algorithm) is the characteristic fluctuation (CFL) of the particle-wave interaction. CFL fluctuations can be reversible and irreversible. The average physical parameters of CFL for a certain elementary characteristic time period are equal to the average thermomechanical macro parameters of the quasi-equilibrium macrosystem DS. Thus, DS is viewed as a physical medium, a macroscopic system formed by a collection of CFLs. They are interconnected by internal processes of CW energy exchange. At the same time, we consider the usual mechanical, physical, thermodynamic and other characteristics of DS. Elastic energy per unit volume of a deformed body W_σ and molar energy, $W_L, J/mol$, volume, are related by the dependence:

$W_L = W_\sigma \cdot Sh$, Where, Sh, m^3/mol, is the molar volume of CFL.

The molar properties of DTT are a new physical dimension of the state of a material as a macroscopic quasi-equilibrium thermomechanical system, along with the usual mechanical criteria. These are additional objective rheological, kinetic and other physical characteristics of the state of irreversible and reversible internal processes in DS. Molar structural and energy characteristics make it possible to estimate the time to destruction (spontaneous, brittle), the rate of degradation of the structural-energy state, the rate and absolute value of irreversible deformations. It is possible to estimate the rate of change in the area of the external macroscopic and internal microscopic surfaces DS, to determine the number of elementary defects (dislocations, vacancies, microcracks) per unit volume, etc. The equations of the theory explicitly contain the process time, temperature, stresses, initial structural and energy molar parameters of the material, etc. Thus, using physical methods, we consider a physical deformed solid. We consider the body and material as a set of elementary physical CW states.

In the wave structural-energy kinetic theory of strength, the mole is an objective physical corpuscular-wave *energy characteristic* DS. The molar volume of a deformed solid is a macro characteristic, denoted by $Sh(\sigma, t), m^3/mol$. Root molar volume of solids γ, m^3/mol, characteristic of the conditional limiting structural-energy state. The molar volume is formed by a set of CFL elementary states in an amount equal to $N_A = 6{,}022 \cdot 10^{23}\ un./mol$ (Avogadro's number). A physical mole is an energy statistical quasi-equilibrium system consisting of a macroscopic number of elementary nonequilibrium states [5]. Usually, a mole is considered as a set of structural units of the medium with mass (atom, molecule, ion, etc.). We consider elementary physical states of molar energy periodic in time and space, the result of the interaction of waves-quasiparticles of energy in a macrosystem. In [6], the main provisions of the physical theory are presented. Each elementary volume contains CFL, representing a nano-microscopic nonequilibrium CW energy system. In this elementary system, there is a continuous process of oscillations (transformations) of corpuscular-wave energy DS (hereinafter briefly CWE). In the elementary molar volume, there is a process of counter movement of CW energy. The kinetic energy of the incoming flow of quasiparticle waves is converted into potential energy of the volume, the potential energy creates a flow of kinetic CW energy outgoing from the volume. An elementary system in this elementary molar volume can be represented as a dipole formed by a sink and a CWE source [6]. A dipole has its own micro parameters associated with macrophysical

parameters: temperature - T, true stresses - σ, elastic energy density и - $W_{\sigma}, J/m^3$, molar energy density of the volume (molar energy) - $W_L, J/mol$ and other parameters of the thermomechanical equilibrium system of a solid and mechanical or other load .

In theory, it is assumed that CFL is the result of a volumetric associated near and far simultaneous interaction, through de Broglie quasiparticle waves, of the entire set of elementary molar volumes of a body of any nature. DS contains microscopic CWE waves with different frequencies, wavelengths, energies, vectors, etc. We use in our formulas a simplified representation, a more accurate model, presumably, this is a corpuscular vortex three-dimensional wave process of CWE motion. This process forms temperature and stress fields. Along with the usual geometric and mechanical parameters, relative volume (linear size), we consider the properties and parameters of the physical volume.

Physical theory has equations, dependencies for solving problems of determining plastic deformations, fracture rate, conditions for reaching the limiting state of a material under variable loads of mechanical and other physical nature, without involving the limiting standard mechanical characteristics [2,3,4]. In SETS, new physical methods and parameters are used in calculations. The equations of the theory allow one to take into account the history, rheology of the load, the influence of various variable factors on strength, plasticity and durability (radiation, temperature, hydrogen potential, electric current, etc.). The influence of these factors (loads) can be analytically represented as outer physical corpuscular-wave energy processes, which in a certain way are summed up with their own physical molar structural-energy properties and TMS parameters. At the same time, the molar parameters of the material and the SETS dependences make it possible to analytically determine each of the known standard mechanical characteristics; for this, we perform virtual mechanical tests according to the standard [7].

Any physical, mechanical and other factor affecting the durability and strength of the material affects the nano-micro structure of the microscopic CW energy fluxes of a solid. Interaction takes place in time and space, the process is considered in physical theory as a load. Different loads can be represented by CW equivalent energy, in terms of molar parameters. The stress field (macroanisotropic) temperature field (macro isotropic) are considered as physical phenomena of a single CW nature. Consequently, physical load is considered to be temperature, electrical, radiation, etc. flow of load energy, expressed in terms of CW molar parameters. Physical strength in SET can be mechanical, radiation, etc. The strength of a material is considered as a process or ability in time to transfer and transform CW energy in a certain finite volume DS, while maintaining its own specified mechanical, physical, and other parameters within specified limits. Our analytical methods use the simplest (engineering) models of physical strength, under conditions of isotropy, uniaxial mechanical stresses and uniform temperature fields, etc. A more accurate model, presumably, is a three-dimensional, anisotropic, vector, corpuscular-vortex wave process of CWE motion. At the same time, physical theory has replaced more than a hundred complex and ambiguous phenomenological theories of strength, proposed a unified, simpler theoretical basis and new methods for solving applied problems of fracture mechanics and materials science.

In SET, new generalized universal physical parameters of the state DS, inre characteristics (inre - in fact, lat.), Derivatives of these quantities are proposed, and their functions are obtained [1].The analytical relationship between physical molar parameters and mechanical parameters of the theory of elasticity, in the simple case, is shown by formula (1).

Let us consider DS as a heterogeneous single-phase (three-dimensional phase) one-component thermodynamic system in a quasi-equilibrium state. Let the function of principal stresses be given with respect $\sigma_1(t)$ to one component of the tensor, $\sigma_1(t) = \sigma(t), |\sigma| > 0$, Pa.. In this case, the state DS can be characterized by generalized physical characteristics, in particular, $Sh(\sigma, t), m^3/mol$ - the molar

volume of quasiparticles of strength. In the molar volume DS for a certain elementary characteristic period of time, characteristic fluctuations of CFL occur, their number is equal to $N_A = 2.23 \cdot 10^{22}, un/mol$, Avogadro's number. CFL is a physical measure of the energy of de Broglie quasiparticle waves, which interact for a specified period in an elementary molar volume, under conditions of thermomechanical quasi-equilibrium of the entire macrosystem [6].

$$W_L = W_\sigma \cdot Sh, \ J/mol, \qquad (1)$$

Where, $W_L(\sigma, t)$ - molar energy, function of state DS $W_\sigma = \frac{\sigma^2}{2E}$, J/m^3, $E -$ elastic modulus. Thus, a solid deformed body is considered as a volume of CFL quasiparticles with a molar energy density corresponding to the elastic energy of a given deformed body. In dependence (1) we see the dualism of the particle-wave approach, a similar method was used in the theoretical substantiation of the Schrödinger wave function. Under the conditions of thermomechanical quasi-equilibrium, there is an analytical connection between the internal energy of a solid as a macroscopic system of elementary particles of mass, on the one hand, and on the other hand, it is the energy of the totality of vortices of waves of quasiparticles CFL in the volume of a given body.

Dependence (2), represents the structural-energy law of the state of a deformed solid, it was obtained on the basis of generalization and analysis of the results of experimental studies of the durability of various solids in a quasi-equilibrium state and a wide range of values $T = const, \sigma = const$ [2,6]. For uniaxial stretching:

$$\sigma \cdot Sh = Gr \qquad (2)$$

Where, $Gr(\sigma, T, U_o, Gr_{o,} t)$ is the function of the structural-energy state of the material, reflects irreversible nano-structural changes in a solid over time under the influence of mechanical, thermal and other loads [6,7]. For uniaxial stretching

$$\sigma \cdot \gamma = W_L \quad (2.1)$$

Where, $\gamma = Sh(t, \sigma = E), \ m^3/mol$ is the root molar volume or structural function of the material. The initial value $\gamma_o = Sh(t = 0, \sigma = E)$ is equal to the Zhurkov structural coefficient [6,7]. This is a physical and mechanical characteristic of the initial state of a nano-microstructure of a solid. The formula for the relationship between mechanical and physical parameters (molar characteristics) of a material:

$$Gr(t) = 0.5E \cdot \gamma_r(t), \qquad Gr_o = 0.5E\gamma_{ro}, \qquad (2.2)$$

The initial value, for pure metals, some solids is determined by the Zhurkov method [8, 9]. For structural materials, it is determined by the rheological diagram of uniaxial tension of the material, to the state of destruction [3,7].

2. The main equation.

In SET, a physical equation was obtained for calculating the fatigue life under non-stationary and complex loads [4,6]. The equation was obtained by the author of the theory as a result of generalization and analysis of empirical dependencies and fundamental experiments of the kinetic concept of strength [8, 9]. The concept formulas are obtained for the condition $\sigma = const$ [9]. Differential equation (3) is

written for an arbitrary given function of true alternating stresses $\sigma(t)$, a one-component structurally homogeneous and stable material.

$$\frac{\sigma(t)d\gamma}{dt} = \frac{RT}{\tau_0}\exp\left(\frac{\gamma_o\sigma(t) - Uo}{RT}\right), \quad j/s\cdot mol, \qquad (3)$$

Boundary initial conditions: $U_o, \gamma_o(0)$. Physical condition for brittle fracture for given tensile stresses $\sigma(t)$:

$$U_0 - \gamma(t_*)|\sigma(t_*)| = 0, \qquad T = const.$$

The solution of the equation allows one to find the value of the root molar volume function - $\gamma(t,\sigma)$, the structural-energy potential $Gr(t)$, the time and the values of the physical and mechanical parameters at the moment of brittle spontaneous fracture t_* or a given limiting state. The physical meaning and properties of the main parameters and quantities $U_o, \gamma_o\ \gamma(t)$ are investigated in [1,2.6].

3. Application of the physical method in calculating strength and durability for alternating stresses and temperatures.

The work [7] shows an analytical method for using the physical theory of strength in calculating the strength and fatigue of carbon steel. Using equation (3), the formulas of the theory, a relationship is established between the physical structural and energy parameters and the standard mechanical ultimate strength and deformation characteristics of the material. To determine the initial physical parameters of the material (boundary conditions of the equation), an analysis of the properties of the experimental rheological functions of stresses and strains obtained at a low rate of deformation of steel under tension to failure was used. Using these parameters, equation (3) and formulas of the theory, the initial structural and energy physical parameters of the strength of steel 45 were estimated. The initial structural parameter $\gamma_o = \gamma(t_{02}) = 1{,}23 \div 1{,}28\cdot 10^{-4}$ m3/mol.The activation energy of destruction to the yield point - $U_{o1} = 1{,}38\cdot 10^5$ j/mol,, to the ultimate strength - $U_{o2} = 2{,}05\cdot 10^5$ j/mol.

Using equation (4) and the obtained initial molar physical parameters of steel 45, γ_0, U_0, fatigue tests of the material are analytically performed, and the fatigue limit of carbon steel 45 is determined σ_{-1p} [7]. Characteristics of 45 carbon steel, as delivered: tensile strength $\sigma_B = 748$, MPa, true tensile strength $S_* = 1173$, MPa; $\sigma_{02} = 412\cdot 10^6$ Pa, , endurance limit (GOST 1497-84) $\sigma_{-1p} = 190$-250 MPa (stretching pulsations). Figure 1 shows the results of a theoretical assessment of fatigue parameters for various specified cyclic stresses and temperature conditions. Numerical methods and our programs for solving equation (3) are used. The assessment of the influence of the load frequency, temperature on durability, endurance limit is carried out. Other mechanical parameters of the strength of steel 45 were also determined by analytical methods. The calculation results are consistent with the reference characteristics of the material.

A program has been developed for calculating the modified mechanical standard characteristics of a damaged material subjected to the action of variable stresses of arbitrary shape and given in time and some other factors.

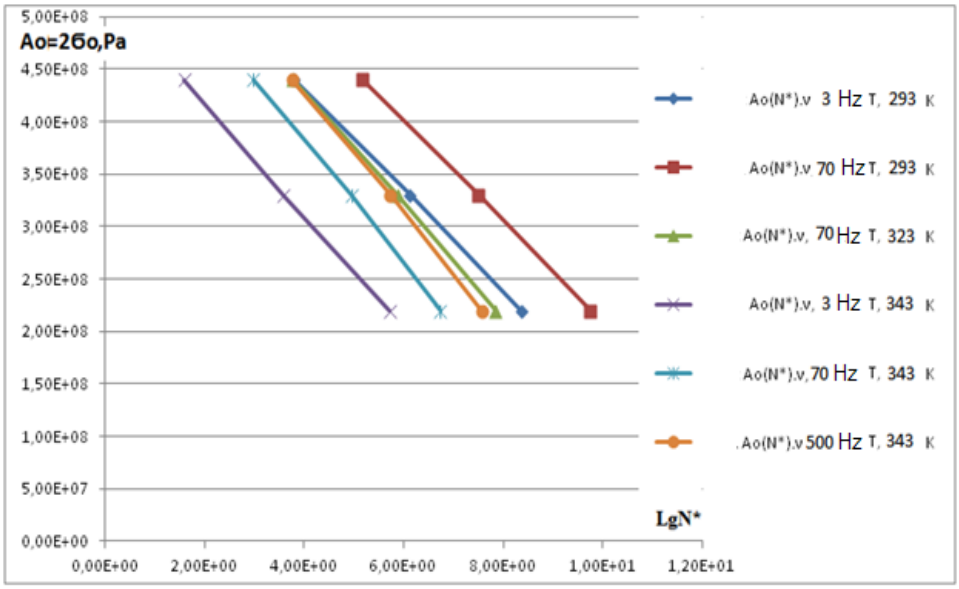

Fig.1. The dependence of the amplitude of the magnitude of the cyclic tensile stress A_0 on the number of cycles to the destruction of the material N_*. 1. Frequencies 3, 70, 500 Hz. Temperature: 293 (20), 323 (50), 343 (70), Celsius temperature in brackets. Form of uniaxial tension cycle stress: $\sigma(t) = \sigma_0(1.001 - \cos B_s t)$. Material steel 45.

Thus, having the load function in true stresses $\sigma(t)$, data on body temperature $T(t)$, initial physical parameters of the material U_0, γ_o, analytical methods of physical theory, it is possible to establish the values of accumulated plastic deformation, damage, predicted time to failure, the influence of the cycle shape on the rate of damage accumulation, and to determine the actual mechanical standard strength parameters for damaged material, etc.

The analysis of the work done showed that the physical approach proposed new convenient and informative methods for solving engineering and scientific problems of the mechanics of strength and fracture of a deformed solid. The results obtained confirmed the validity of the physical wave-particle model of the strength of materials. At the same time, the work done has shown that the determination of the main physical parameters of a material γ_o, U_0 according to the rheological stress-strain diagram of a sample is a laborious and expensive, sometimes inaccessible procedure. Therefore, the following task was set, to develop an engineering method for determining universal molar physical parameters, using the results of modern methods of kinetic indentation of material according to the ISO 14577 standard.

4. Energy measure, similarity criterion, universal scale and unit for measuring the physical hardness of a material.

Using the methods of the physical structural-energy theory of strength, we analyzed the main methods for determining the hardness of different materials. The properties of the force diagram, the energy and geometric parameters of the kinetic indentation of the material were investigated according to the ISO 14577 standard [10]. The main part of the considered experimental and methodological material is from the monograph and articles of professor KHNAHU V. Moshenok [11,12].The combined analysis made it possible to make the final conclusion that the existing standard methods of one-step and kinetic indentation are based on an empirical approach, in which there is no physical principle for determining the hardness of a material. Historically, in different versions, the empirical hardness number is based on the value of the ratio - F / S, where F is some value of the force acting on a certain conditional contact area S and the conditional volume of the deformed material. Essentially, the value of the conditional pressure, the specific force, or the conditional stress in the material is considered, in various combinations of its calculation. Then this value is considered as the basis of the criterion or hardness number. Standard

methods offer various variations, methods of selection, recalculation, correlation of the magnitude of the conditional stress. Then, this empirical value is postulated as a hardness number. In empirical methods, a number of methodological problems have accumulated, contradictions in the comparison of different hardness numbers (different indenters were used, etc.), a dimensional effect of “different signs” arose, etc. [11].

From the point of view of physics, the conditional pressure (empirical hardness) is an ambiguous and unstable characteristic of the process in the "material - indenter - load" system, especially for different instruments, different kinetic modes, including one-step indentation.

In our work, a physical approach is proposed. We use a standard kinetic indentation diagram, which can be obtained with different instruments and different maximum forces. Physical hardness and physical theory of strength are based on a common basis - the corpuscular-wave structural-energy kinetic theory of solids. To determine the physical hardness number, an analysis of the density function of irreversibly dissipated mechanical energy is used. Energy density is the work of the indenter divided by the amount of activated volume (conventional geometric or physical). Consider the kinetic force diagram, the parameters of the tool geometry and the activated (displaced) material during indentation. Physical hardness is based on the function of the density of the dissipated energy from the displacement of the indenter, the function of the state of the "material - tool - load" system. This system will be denoted below as TMSI (thermomechanical indentation system).

We have developed an analytical basis for creating a standard universal method for determining physical hardness, regardless of the magnitude of the force, the shape of the tool, etc. [10]. The initial data for the physical method are the parameters of the instrument and the physicomechanical parameters of the selected process of the standard macro, nano-micro mode of kinetic indentation. The physical approach made it possible to exclude the size effect and the properties of ambiguity inherent in empirical methods of one-step mechanical and kinetic indentation. Similarity criteria and methods for comparing different numbers of empirical hardness are formulated. The material is characterized by one number (measure) of physical hardness, which does not depend on the tool, method, kinetic indentation mode. In the physical and empirical methods, the dimension of the hardness number, in formal operations with the dimension, coincide. But these are fundamentally different characteristics of the physical state of DS, represented as TMSI. The number of physical hardness is a certain value of the function of the generalized specific power of the irreversible process of changing the structural and energy state of TMSI. Empirical hardness is specific strength (in different interpretations), an ambiguous characteristic of the state of the TMSI.

From the physical analysis of the kinetic indentation data, a new structural-physical parameter of the material is obtained - Dn, N/m. This hardness parameter is analytically related to the physical molar parameter of the strength and durability of the material Gr. Thus, using the analysis of the force function of the kinetic nano-micro indentation $F(h)$, an analytical relationship was established between the important physical and mechanical parameters of hardness and strength of the material.

Using the data of the standard kinetic indentation process, it is possible to determine the value of the universal physical hardness and the value of the universal physical structural-energy parameter of the strength and durability of the material. These physical parameters and dependences of the theory allow one to analytically find the time and conditions for the occurrence of the limiting state for a given variable load, material of different nature. At the same time, it is possible to analytically establish the standard limiting mechanical parameters of the material directly in the elements of the existing structure [10].

Briefly the main stages and results of our work. Initially, an analytical analysis of the physical properties of the force function F (h), obtained according to the ISO 14577 standard, was carried out, as well as an analysis of the functions of the parameters of the volume and area of the contact surface during

indentation. Various tools, materials and modes are considered. To describe the strength function, the approximation equations proposed in [11] were used. The results of our work have been published [10].

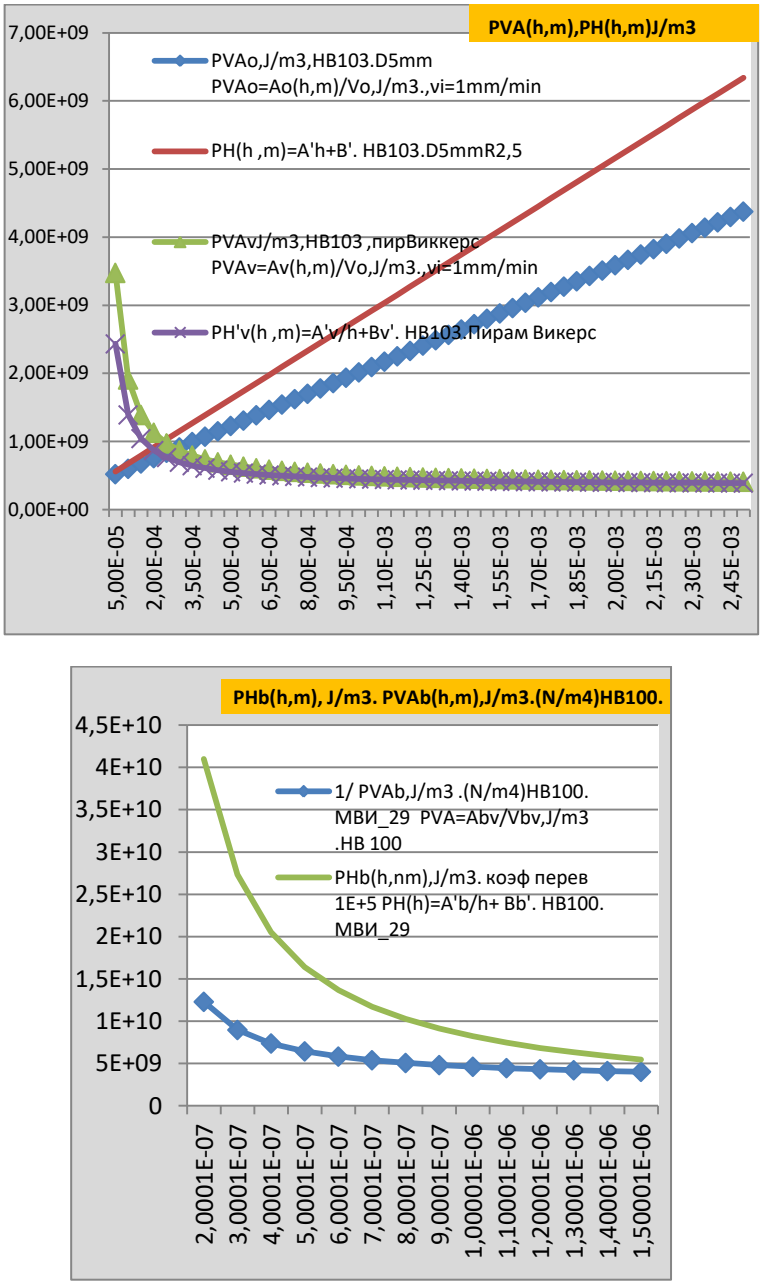

Fig. 2. Comparison of the nature of the functions: a) energy density function $PVA_0(h)$, differential hardness $PH_0(h)$, indentation by a sphere D5mm, Vickers pyramid, Test unit HB103, b) Berkovich pyramid, Test unit HB100, $PVA_v(h)$, $PH_V(h)$ Constructed according to the results of processing the functions F (h), data [11].

Using the criteria and methods SET in [10], new physicomechanical parameters and characteristics of the process of formation of the contact surface S (h) and the activated volume V (h) of the material during indentation were determined. New geometric concepts of the indentation process are used: conditional area, physical contact area, conditional and physical activated volume, etc. unit volume of activated material. The relationship of the specific mechanical work A (h) of the indenter with different objective geometric characteristics of the process, during its movement in the material, was considered.

We consider two different concepts: the outer surface (contact) and the physical surface of the boundary of the activated volume of the internal structural-energy CW states of the material, etc.

Three options for determining physical hardness as a measure of the energy density of kinetic indentation were analytically considered: average integral density PVA (h), differential PH (h), nano-micro differential $PHN(h)$. The shape and size of the tool, the comparison criteria, are considered additionally, within the framework of the physical approach to determining the hardness.

$$PVA(h) = \frac{A(h)}{V(h)} = \frac{\int_0^{h(t)} F(h)dh}{V(h)}, \text{ J/m3.} \qquad (4.1)$$

Where, $PVA(h) = \frac{A(h)}{V(h)}$, J/m^3 - is the average integrated density of the indentation energy.

$V(h)$ - displaced, activated volume, $F(h) = a \cdot h^n + b \cdot h$, load on the indenter, approximation by the polynomial proposed in [11]:

$$PH(h) = \frac{dA(F,h,T,E..)}{dV(F,h,T,E,...)} \approx \frac{\partial A(h)}{\partial V(h)}, J/m^3 \qquad (4.2)$$

Where, $PH(h)$ is the function of differential energy density (PH - phisics hardnes) , $dV(h)$, $\partial V(h)$ partial differentials and their partial derivatives, T, E -parameters of the material.

$$PHN(h) = \frac{\partial A(h)}{\partial V(h)}, \quad (4.3)$$

Where, $PHN(h)$ is the function of physical nano-micro-kinetic indentation, under the precondition, $1 \cdot 10^{-21} < Vpr < 1 \cdot 10^{-18}$ m3, V_{pr} is the nano-micro activated volume. Nano mode - lower value. Micro mode is greater. In Fig. 2 functions of integral energy $PVA(h)$ density and physical differential hardness $PH(h)$, indentation of the standard measure HB 103, sphere D5mm, Vickers pyramid, Berkovich pyramid according to [11].

Physical hardness, definition (briefly).

Specific amount of energy spent on the irreversible process of formation of a unit of area of the contact surface of the test material, as a result of mechanical pressure and displacement of the body of an indenter of a certain shape and size into the material under study. $PH(h)$,J/m3 - function of physical differential hardness, differential energy density of kinetic indentation of the material. Differential hardness is also the generalized specific power of irreversible structural and energy transformations of the activated volume of material during its mechanical movement, the formation of a new surface, under the pressure of a moving indenter.

The number of physical differential hardness $PH_{st} = PH(h_{st})$ is the value of the hardness function at the reference (standard) depth of movement of the spherical indenter h_{st}. To compare the physical hardness obtained by a different indenter or mode, a physical criterion for the similarity of the process is proposed:

$$X_{sv}(h) = \frac{S(h)}{V(h)}$$ - specific area of indentation.

Physical analysis of kinetic indentation, three methods.

Based on the results of the analysis and generalization of the properties of the specific energy functions of kinetic processes obtained for different methods and tools, on different materials, the standard processes of kinetic non-recovered indentation were divided into three different methods for determining the universal differential physical hardness of a material (physical hardness).

1. **The first method** is reference indentation by a sphere (macro mode, surface mode).

2. **The second method** is indentation with a pyramid, a cone (sharp instrument). This indentation method is combined (two-tier), processes nano micro and macro. The initial stage is nano-micro, then the joint process.

3. **Third method.** Nano-micro indentation with a tool of various shapes.

From the analysis of the properties of the functions of empirical, physical average integral and differential indentation energy density, it follows that the differential indicator is more generalized (integral) informative and stable. The differential density of the indentation energy has become the basis for the formation of the criterion of physical hardness, a universal unit of hardness. Studies have shown that indentation by a sphere can be viewed as a reference process for measuring the physical hardness of a material. Corresponding calculations of physical hardness of standard measures were performed [10]. For macrokinetic indentation with a sphere D> 2.5mm, the physical hardness is invariant to the diameter of the sphere. This macro process is called "laminar indentation".

To maintain the similarity (comparison) of processes, when changing the parameters of the geometry of the indenter, the depth of indentation, the similarity coefficient is used in the calculation, it takes into account the change in the parameter X_{sv}. The use of the similarity criterion is considered when comparing the physical number of hardness for different exemplary measures. Method 1 (sphere indenter) and method 2 (Vickers pyramids) are compared [10]. Algorithms have been developed for bringing the results of indentation by different methods and indenters to the value of the standard of physical hardness of a given material.

On the basis of the 1st indentation method, dependencies were obtained for calculating the reference unit of absolute, relative physical differential hardness, and a universal indentation hardness scale was proposed.

To study the properties of physical hardness, select a unit of measurement, create a universal scale of hardness, etc., a preliminary concept of a reference standard process was introduced - PH_{ST}. This is the value of the physical differential hardness of indentation by the sphere when the tool moves *to the reference* (*approved by the standard*) *depth*. In the studies, the value is preliminarily taken:

$$h_{st} = 0{,}25\text{mm} = 0{,}25 \cdot 10^{-3}\,\text{m}.$$

In our work, the dependences are analytically obtained for comparison, translation into a universal physical unit of measurement of the number of surface empirical hardness of the material.

Studies have shown that the scratching method is correctly comparable with the kinetic indentation data and that they meet the physical criterion of similarity. Consequently, these methods are analytically

comparable and interchangeable when solving applied problems. The results of these different techniques can be displayed in the same physical units of hardness.

The physical method for determining the hardness number according to the kinetic diagram ISO 14577 made it possible to exclude ISE (Indentation Size Effect), which is present in empirical indentation methods.

In [13], the principle of indentation by a truncated cone by the Kelvert Johnson method, proposed in 1859, is described. The essence of this method is the indentation of a truncated cone of constant dimensions to a constant set depth. This method represents a special case of the physical method for measuring kinetic hardness. The physical reference hardness value, up to a constant factor, is equal to the Calvert Johnson hardness. Their method was lost over a long period of development of indentation in different directions. We proposed to name the universal unit of physical hardness in honor of the authors of this method:

$1.0\ \mathrm{CD} = 1 \cdot 10^7\ \mathrm{J/m3}$

$1.\mathrm{CD}$ - one ("kedzh", "cadg").

For example, the hardness of the reference block 103HB corresponds to approximately 100CD units of physical hardness.

In [10], calculation formulas, a comparison method, a similarity coefficient, etc. are given. Let us determine the value of physical hardness by the second method, in universal units, using the Vickers pyramid, measure 103 HB. In the dimension of energy density we have: $\mathrm{PHV_{st}} = 0.45 \cdot 10^9\ \mathrm{J/m^3}$. Using the basic formula (4.3), the comparison method, for the Vickers pyramid we obtain the similarity coefficient VTR = 2.3. Applying the similarity criterion to the physical hardness $\mathrm{PHV_{st}}$ number obtained by the second method with the Vickers pyramid indenter, for a hardness measure of 103 HB, we find the reference value $\mathrm{PH_{st}}$:

$$\mathrm{PH_{st}} = \mathrm{VTR} \cdot \mathrm{PHV_{st}} = 2{,}3 \cdot 0.45 \cdot 10^9 = 1{,}035 \cdot 10^9\ \mathrm{J/m^3}$$

This value slightly differs from the physical hardness obtained by the first reference method on a sphere at an exemplary measure of 103 HB. In universal units of hardness, we get approximately 100CD.

The physical hardness of the main structural materials is in the range of 1-1000CD, regardless of the type of indenter and test mode. The ratio of the values of nano-micro and macro physical hardness is some constant value, subject to the conditions of similarity.

5. Universal physical equation of nano-micro kinetic indentation. Physical model of the nano-micro process.

The universal physical equation of nano-microkinetic indentation is of interest for assessing the strength and durability of materials of structural elements using a new accelerated physical method. It was obtained on the basis of a physical model of the process of nano-micro indentation with a sharp indenter developed by us. Let's consider the main stages of this work.

Calculations, analysis, generalization of results and analytical modeling of physical processes of nano indentation showed that the initial section of the curve, physical and empirical hardness, namely, the segment before the inflection of the graph and the initial segment of the stabilization of the process

(reaching the horizontal) can be described as the sum, superposition of two processes, by the equation [10]:

$$HIN(h) = \frac{Dn}{h + B} + HI(h), J/m^3 \quad (5)$$

Where, Dn, B, - parameters of the equation $HI(h_{st})$ of empirical hardness of kinetic nanoindentation, depend on the material, tool and speed of indentation.

$HI(h)$ - process function or reference value of empirical hardness, for the macrokinetic indentation of a given material.

$\frac{Dn}{h + B} = NI(h)$ - a function of the physical process of kinetic nano indentation. The formula was obtained on the basis of a physical model of a nano-micro process of forming a molar activated volume of a solid by a sharp indenter [10].

$Dn, N/m$ - is the structural-physical parameter of the material.

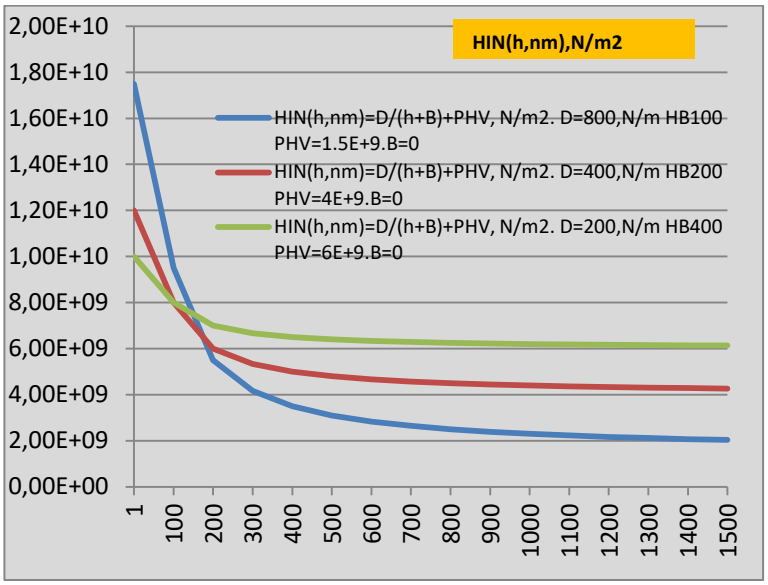

Fig. 3. Analytical modeling of physical functions of nano-micro indentation HIN (h) using equation (5). Diagrams of indentation of three hardness measures HB100 / 400/660, indenter is a Vickers pyramid, parameters Dn, PH = PHV, B = 0, method of addition of functions of nano-micro and macro processes are given.

Figure 3 shows the results of analytical modeling of the physical function of the conditional pressure of nano indentation HIN (h), Pa, in the first approximation, using equation (5). The graphs are constructed for three conditional materials of different hardness HB800 / 400/200. For comparison, Fig. 4 shows the experimental-analytical diagrams of empirical hardness: a) obtained on the experimental setup for nanoindentation by Professor Moshenok [12]; b) the diagram is constructed analytically using the formulas and power diagram from the monograph [11].

In the physical model of the nano indentation process Fig. 4b, the pressure value NI (h) in the activated volume depends on the structural physical parameter Dn and the depth of

displacement h. The Dn parameter characterizes to a greater extent the structural and physical properties or nano-micro hardness of the material.

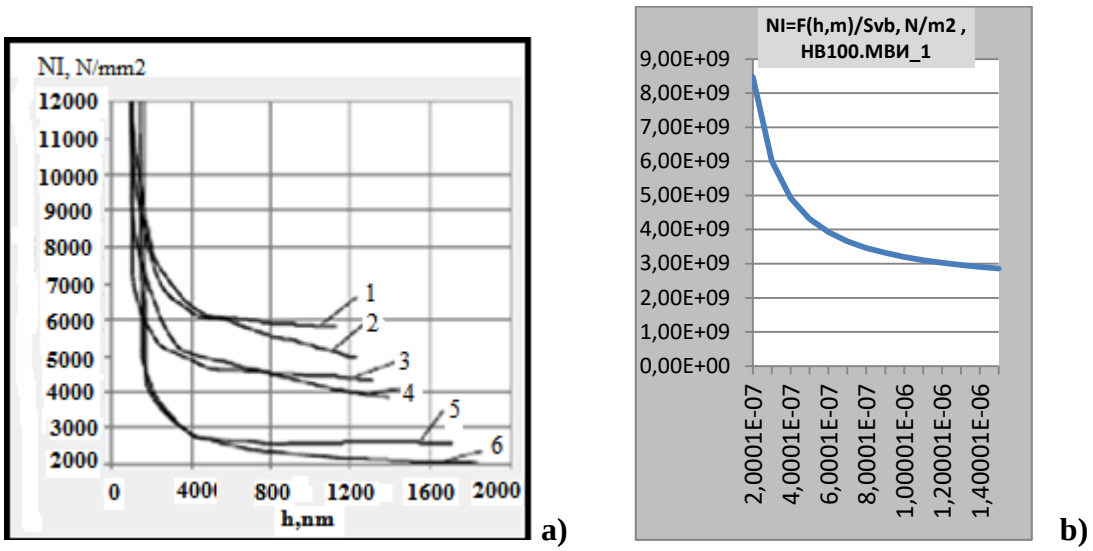

Fig. 4. Surface kinetic nanohardness NI (h) of steel samples: a) 1 - 788HV, 2 - 508HV, 3 - 73.2 HRA, 4 - 411HB, 5 - 28.9HRc, 6 - 103HB [12]. b) diagram $\mathbf{NI(h)= F/27h^2}$ Berkovich pyramid, an exemplary measure HB103, built using the approximation of the experimental function F (h) [11].

In the empirical method, the pressure is determined by the formula HI = F / S, where the force on the indenter is F and the value of the conditional contact area S. For nano-micro processes, in calculating physical hardness, it is incorrect to use the concept of a geometric contact area. Equation (5) simulates the CW process of irreversible changes, when indenting with a sharp instrument, in *a physical* nano-micro-activated volume of material. The equation can be used to approximate empirical indentation plots obtained by standard techniques (Fig. 4). We assume that at the first stage of nano activation of the latent energy of the material structure, the parameter Dn more accurately shows the pressure function than the empirical method. The work [10] shows an analytical connection Dn with the nature of the force function F (h) and the value of the hardness number. For the subsequent practical use of the physical method obtained by us, additional extended studies are required.

6. Model and function of structural and energy transformations of the material, nano indentation by SI instrument. Leading process.

Equation (5) was obtained on the basis of our hypothesis of superposition of two conditional variants of physical CW processes of kinetic indentation by the SI instrument. The first SI indentation process is "turbulent", it is irreversible destruction of the nano - microstructure of a solid [10]. The second variant of indentation is “laminar” mode. Irreversible deformations of the shape and contact surface of the activated volume, conditional sphere, $h > 1.0mkm$.

Studies of the properties of the diagrams of hardness HI (h), NI (h) suggest that the drop in the specific molar power of irreversible destruction of the nanostructure in the physical volume of activation occurs up to the inflection point of the diagram NI (h). The formation, relaxation of the physical system of characteristic fluctuations of the nano-indentation volume (relaxation)

occurs in the region, $h < h_r$, h_r = 5-100 nm. The relaxation time depends on the material and surface preparation. At the moment when the top of the indenter touches the surface, a local "explosive" process of release of the latent melting energy of a solid is activated. During the relaxation period, the energy density is much higher than in the laminar process of macroindentation [10]. Analysis of experimental data showed that for structural materials the physical volume of nano-microactivation Vp is approximately in the range of values $1 \cdot 10^{-21} < Vp < 1 \cdot 10^{-18}$ m3. A high density of CW energy is activated in the physical volume Vp. This is the result of the concentration in it of irreversible destruction of bulk nano-micro-structural associated structures (lattice, molecule, cluster, etc.). The volume Vp surrounds a relatively cold body, the boundary of the physical volume has a small surface area, it reflects the internal waves of the CW process. This is the border of different CW processes. Initially, the relaxation stage, there is not enough dissipation of the released energy. The energy of destructive fluctuations is accumulated in a small area. At the same time, the depth of movement of the tool h, the volume of the mechanically activated region Va, the area of mechanical contact and the conditional physical surface of the volume grow. The absolute number of powerful destructive irreversible fluctuations in this volume grows, and the molar parameters of TMS change. Calculations show that from the moment $h > h_r$ the dimensionless rate of energy release becomes less than the dimensionless rate of growth of the activation volume, therefore, the energy density decreases. In the physically activated volume of the material Vp, in front of the top of the sharp indenter, the energy density and conditional pressure HI (h) begin to drop, Fig. 5. Thus, in the activated volume Vp, as a result of sequential scanning [14] of the molar energy parameters (CW parameters of the energy of characteristic fluctuations), the moment of formation of a physical state with molar parameters characteristic of a given material necessarily comes. A physically activated nano region of destructive energy fluctuations, the root molar volume of characteristic fluctuations V_μ, is formed. The process can be schematically indicated $Vp \rightarrow V_\mu$. The physical parameters of the molar root volume V_μ depend on the energy of the initial structure of the material, the rate of indentation, parameters and properties of the body Vp, as well as the surrounding volume (thermal conductivity, elasticity, etc.). The main quality of the molar root volume is that it is similar to the state of an isotropic homogeneous solid with its own characteristic physical parameters. The shape of the indenter in the initial period of formation V_μ is, presumably, of secondary importance. The magnitude of the molar nano-activated volume V_μ of a given material is an objective physical and mechanical characteristic of a material, a function of the physical properties of substances in a given system and a certain specific power of the irreversible process of releasing the CW energy of the SES material during the movement of the indenter. We assume that at the point of inflection of the physical and empirical diagrams of nano-micro indentation, the process of formation of the characteristic molar volume is completed V_μ. Dn - parameter of the hyperbola shape, integral characteristic of the process. We assumed the presence of a relationship between the root molar parameter of the structure Gr and the physical parameter of the material hardness Dn.

Process model. In front of the moving top of the SI indenter, at the moment of contact with the material, a nano-region appears - a physical activated volume with a high density of fluctuation energy.

The initial process of nano indentation is considered from the standpoint of the physical structural-energy theory of strength [2, 10]. In front of the top of the SI indenter, an area of high density CW of energy of quasiparticle waves is formed, an area of high activation of destructive processes. Let's designate this physical volume - $\mathbf{V_{LP}}$. We assume that the process of leading **structural and energy transformations (LP - leading process)** is taking place in it. Experimental and analytical studies indirectly indicate the stability and individuality of the main parameters in this area. In Fig. 5 schematically shows the main stages of the formation and movement of the LP region of nano-micro indentation.

High initial energy $\mathbf{V_{LP}}$ density as a result of the accumulation of released energy of irreversible destruction of the initial structural-energy state (SES) of the material. During this period, the structure of flows of stable ordered vortex and oscillatory motion of the energy of quasiparticle waves in the volume $\mathbf{V_{LP}}$ is destroyed. This initial state in physical theory is considered as the initial, root CW energy density of the nano-microstructure of a solid. In the theory of metals, this process is associated with the release of the latent heat of fusion. A feature of the wave process in a volume $\mathbf{V_{LP}}$ is the ability of the outer physical boundary of a given volume to reflect inward (return) the waves of the released CW energy. In this volume, local physical conditions are created for the adiabatic process. A similar role of the boundary of the shock wave physical process can be seen in the Prandl Glauert effect. In the classical atomic model of the strength and fracture of solids, short-range interaction is considered; therefore, such a physical model of the process is impossible. In a simplified physical model, we assume that the volume $\mathbf{V_{LP}}$ has its own homogeneous, isotropic high thermodynamic and energy parameters. In a number of cases of nanoindentation, jumps in the force diagram are observed experimentally [14]; presumably, we observe local anisotropy of the CW process. On the physical nature and conditions for the formation of a stable state, homeostasis of irreversible transformations of the nanostructure of a solid in the work [15]. With the mechanical movement of the sharp indenter, there is a simultaneous movement, contact boundaries and movement of the region V_{LP}. In fact, the movement of the SI vertex causes the translation of the state of highly active irreversible processes of the nanoplastic LP zone into the depth of the body. The main energy of the activated volume V_{LP} is transferred not by the mass of particles, but by quasiparticles of vortex wave nano processes. The physical volume V_{LP} is characterized by a large value of the energy density of an irreversible process, a large contact pressure or ball tensor, and a large temperature.

In the work of I.D. Ibatullin [15], the experimentally confirmed local processes of the occurrence of high temperatures at the points of contact of structural elements of solids during friction and force contact of metal surfaces are considered. According to our assumption, as a result of the force contact of the surface of the indenter and the material, high-temperature and high-pressure elementary nano regions are formed, in which the melting temperature of the contacting bodies is reached. Analysis of the experimental results indicates the anisotropy of these parameters and states of the material. Elementary states of fluctuations during the subsequent movement of the top of the indenter form a homogeneous system of a highly activated state of matter. Modern experimental research confirms this. Some of the results of our research [10] indirectly confirm these assumptions. For instance. Determine the energy density of a metal when pure iron is melted using the average reference values. Specific heat of fusion of pure iron $\lambda = 270 \cdot 10^3 \mathbf{J/kg}$, density $\rho = 7870 \mathbf{kg/m^3}$ **NI(h)**, we can easily obtain the specific volumetric heat of fusion of iron $\lambda_v = 2{,}1 \cdot 10^9 \mathbf{J/m^3}$. This value is consistent with the PVA energy density for macro-identifying steels. Energy density of nano indentation of steels in the range up to 400 nm $PVA = (4 \div 100) \cdot 10^9, J/m^3$. As you can see, the value of the physical nanohardness of metals exceeds the value of the specific heat of fusion. Estimation of losses due to heat dissipation

showed that in the initial SI indentation period the energy is sufficient for the transition from the solid state of the local volume of a solid to a quasi-liquid one. A similar result was obtained for aluminum and tungsten.

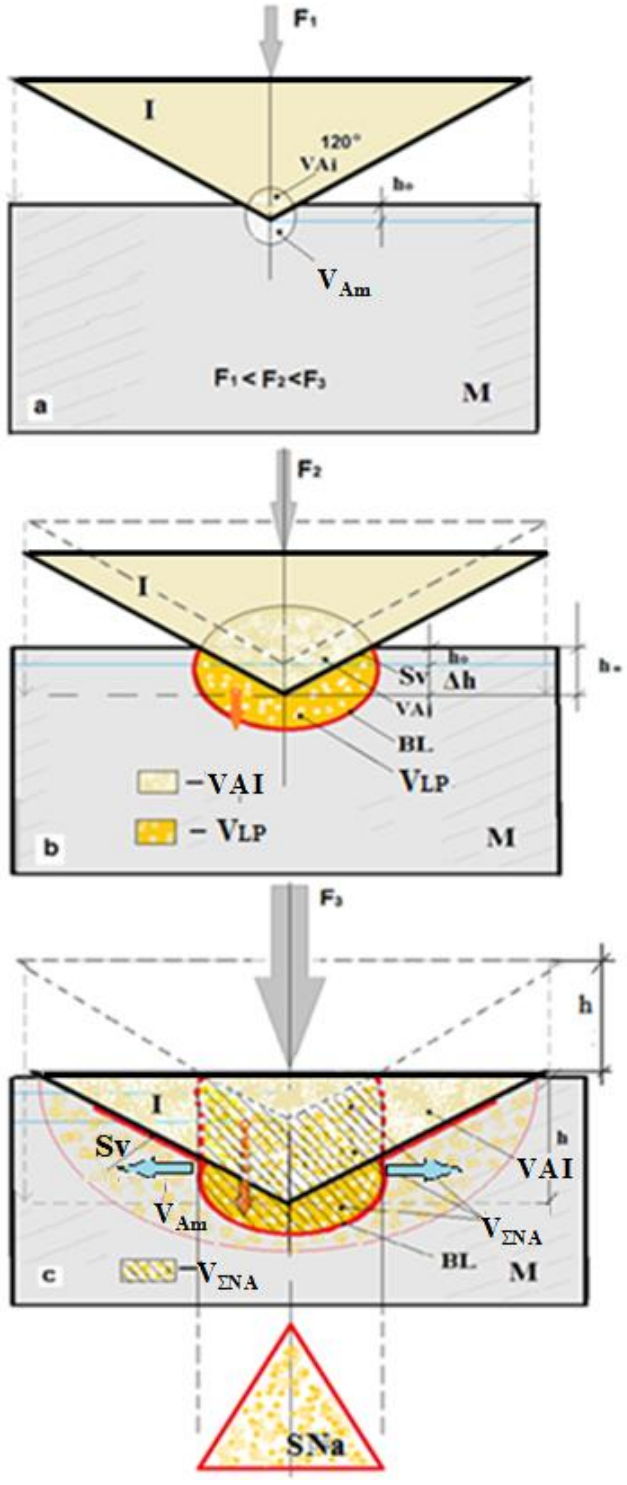

Fig. 5. The model of the formation of a nano-activated volume of material, the **leading process** of structural and energy transformations by a sharp indenter, the Berkoich pyramid: a- the initial stage to a depth of ho; b - formation of an activated $\mathbf{V_{LP}}$ **leading process** area; c - translation of LP activation with high energy density, formation of the total volume $\mathbf{V_{\Sigma NA}}$; The blue arrows show the LP energy dissipation.

Legend in Fig. 5:

I - indenter; **M** - material for indentation; $\mathbf{F_i}$ - effort on the indenter at different periods of the activation process; $\Delta\mathbf{h}$ - displacement of the indenter in a stable activation process; **VAI** - activated volume in the body of the instrument; $\mathbf{V_{Am}}$ - the activated volume of deformation processes in the body of M; $\mathbf{V_{LP}}$ - the activated physical volume of the leading process of irreversible structural and energy transformations; S_{LP} - the surface of the activated volume $\mathbf{V_{LP}}$; $\mathbf{V_{\Sigma NA}}$ - accumulated total volume of activation as a result of Δh displacement of the indenter; **Sv** - is the active contact surface of the indenter and the imprint; **SNa** - is the projection of the nano-activated volume of the trihedral pyramid indenter onto the plane of the material sample; BL - surface $\mathbf{V_{LP}}$.

In the nano indentation model, we represent the depth h as the characteristic size of the radius of the sphere of the physical nano-activated volume $\mathbf{V_{LP}(h)}$. In the volume $V_{LP}(h)$, presumably down to the depth $\mathbf{h = L_{prmi} = 1 \cdot 10^{-6} m = 1.0 mkm \approx 1000 nm}$, there is a comprehensive compression of the material. The pressure (stresses) in the activated volume $\mathbf{V_{LP}(h)}$ along the three axes of the tensor are assumed to be the same. The pressure in the volume $\mathbf{V_{LP}(h)}$ of nano-micro indentation, up to a depth of about 1000 nm, is set by the function of the leading process of structural and energy transformations for the SI instrument:

$$NI(h) = \frac{Dn}{h + B}, \text{ Pa} \quad (6)$$

Where, Dn, N / m. $B \geq 0$, m - constants of nano indentation by SI instrument, depends on the material, shape of the instrument, temperature and speed of indentation.

Using the physical analysis of kinetic indentation, an analytical method for assessing new physical integral universal parameters of material hardness is obtained. The analytical dependence of the physical and empirical numbers of material hardness is determined. The basis of the method for determining the universal physical number of hardness is developed, the physical equation of nano-micro indentation and a new structural-physical parameter of the nano-micro hardness of the material are obtained.

7. The ratio of the structural-physical parameter of hardness and the structural-energy parameter of strength and durability of the material.

To describe the experimental dependences of the process of nano-micro-kinetic indentation and the process of destruction of nano-micro-thin samples of material under tension, a general physical model and equations (5), (6) of the particle-wave energy CW process were used. When comparing the obtained analytical functions of these dependencies, their similarity was established. As a result, we obtained formula (7), which reflects the assumed relationship between the structural-physical parameter of nano-micro hardness Dn and the structural-energy parameter of material strength..

$$Gr = k_G Dn, \quad J / mol \quad (7)$$

Where, k_G, m^2 / mol - is the normalization coefficient for the conversion of physical hardness into the dimension of the structural-energy parameter of the strength of the material.

The main stages of substantiating formula (7). In Fig. 6 shows the graphs of the functions of four different physical and mechanical processes, reflecting the irreversible change in shape, destruction of the structure in the bulk of the material. Shown is the dependence of pressure, stresses of different signs, on the volume or characteristic size, different material environment (A, B, C, D):

A. law of state of an ideal gas (isotherm), mass is constant:

$$pV_\mu = G(T, M_\mu). \quad J / mol, \quad T = const, \quad M = M_\mu = const, G = const \quad (8.1)$$

B. The law of the structural-energy state of a deformed solid under constant temperature conditions (isochronous - isotherms):

$$\sigma \cdot Sh = Gr, J/mol, \; Gr = const \qquad (8.2)$$

C. Physical equation of nano-micro indentation:

$$NI(h) \cdot h = Dn, \; N/m, J \qquad (8.3)$$

Where $h \sim V_{ap}$, V_{ap} is the physical volume of activation of the destruction of the nanostructure.

D. True tensile strength $\sigma_*(h_v)$ of a nano layer of pure metal deposited on the surface of an elastic polymer, layer thickness h_v:

$$\sigma_* h_v = D_\sigma, \quad N/m. \qquad (8.4)$$

It is easy to see the similarity between these functions. We assume that each process is based on the nano-micro corpuscular-wave mechanism of irreversible transformations of the CW energy of the nano-micro structure and the geometric shape of a small activated volume of the material medium. Each anisotropic or isotropic quasi-equilibrium process in Fig. 6 is characterized by its constant potential of the work flux density (G, Gr, Dn, D_σ) or the pressure energy flux. Formally, in each variant, the product of a function and an argument is a constant. An ideal gas, in contrast to a solid, has the potential of an isotropic structural-energy CW process [6]. The graphs of all functions in Fig. 6 are similar, they represent hyperbolas, the equation has the form $Di = X \times Y$, where Di is some constant of the product of two variables X, Y. Property of functions: the product of a function and an argument in a certain physical process is equal to a constant, we have an invariant of the product of two variables at each point of the function, with constant macro parameters of the selected thermomechanical system.

Derivation of formula (8.4). Using the experimental properties of destruction of nano-coating of pure metal [16], as well as nano-micro indentation of pure metals, the function of the structural-energetic nano process of irreversible deformation and destruction of the material, independent of the sign of stresses, was obtained. An analytical relationship has been established between the magnitude of the physical activated volume and destructive stresses [10]. In [16], experimental dependences of the tensile strength of a pure metal nanocoating are shown. A nano-layer of metal is applied to the surface of a strong polymer, which is elastically stretched until the metal coating breaks down. The dependency was received:

$$\sigma_* = \frac{L\sigma_o}{4h_v} \qquad (9.1)$$

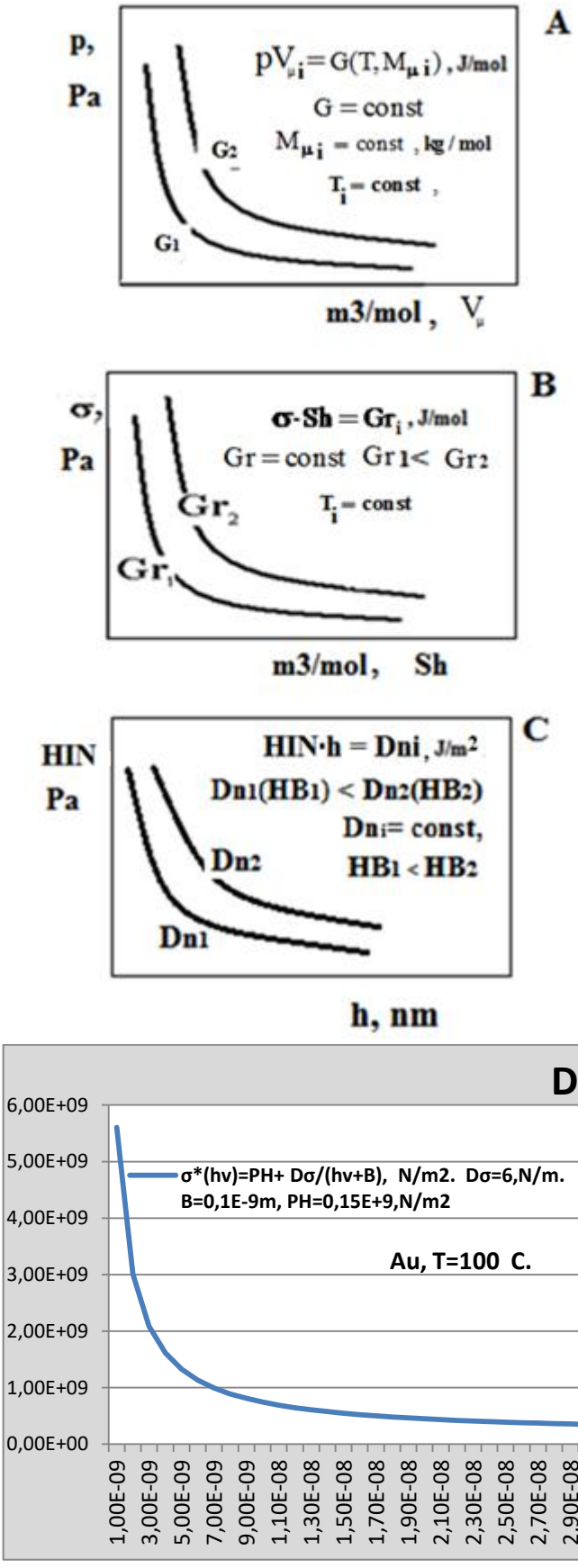

Fig. 6.Graphic display of the structural-energy law for different thermomechanical systems: A - the law of state of an ideal gas, isotherms, constant mass; B - the law of the structural-energy state of a deformed solid (isochronous -

isotherms). C - physical equation of nano-micro indentation. D - approximation by equation (5) of the experimental dependence of the true ultimate strength of a pure gold $\sigma_*(h_v)$ nano layer on its thickness hv [16].

Where, σ_o is the stress in the polymer at 100% deformation, L is the characteristic size of identical fragments of the destroyed metal coating. From (9.1) transforming, we get:

$$\sigma_* = \frac{D_\sigma}{h_v}, \text{ Pa.} \qquad (9.2)$$

Where, $D_\sigma = \frac{L\sigma_o}{4}$, N/m - is the constant of the structural-physical state of the thermomechanical metal-polymer system. Transforming (9.2), we obtain (8.4).
Formula (8.4) is obtained by elementary transformations of dependence (9.2). The formula is a good hyperbola approximation of the experimental data [16]. In Fig. 6D approximation by equation (8.4) and (5) of the experimental dependence $\sigma_*(h_v)$ for a pure gold nanolayer, T = $100C^\circ$, hyperbola with a shift by the value of the PH constant, data [10].

In calculating the molar energy parameter of the structure Gr, for normal operating conditions of materials, using the data and equation (5) of indentation, one should take into account the anisotropy and high physical parameters (pressure, temperature) in the activated volume of nano-micro indentation.

An example of using formula (7) to determine the normalization parameter. Alloy 1201T1, the structural-physical indentation parameter $Dn = 8 \cdot 10^3, N/m$ is determined by formula (5), The parameter $Gr_o = 2{,}77 \cdot 10^7 J/mol$ is obtained in [10]. The value $\gamma_o = 0{,}195 \cdot 10^{-3} m^3/mol$ is obtained by formula (2.2). From these results and formula (7), we obtain the conversion factor:

$$k_G = 3{,}5 \cdot 10^3, \ m^2/mol.$$

Preliminary calculations of the influence of the main physical parameters of the state of the material on the value $Gr(T, \sigma_{sh}, \sigma, E)$, where σ_{sh} is the stress of the spherical tensor, have shown the theoretical possibility of applying the formal transformation of the dimension in dependence (7). An analytical assessment of the influence of high thermomechanical parameters of the nano-micro indentation process showed the predicted value of the parameter growth Gr in $k_p \approx 10^3$ times. Taking into account the influence of the growth of physical parameters during indentation, we obtain from (7) the refined formula:

$$Gr = k_p \bar{k}_G Dn, \quad J/mol \quad (10)$$

Where, $k_p \approx 10^3$, is the correction coefficient of growth Gr, taking into account the difference in the physical conditions of indentation and stretching of the nano-micro sample. As a result, we get the normalization factor $\bar{k}_G \approx 1{,}0 \ m^2/mol$.

From a comparison of graphs and formulas, one can see that dependence (8.4) is similar in form and content to the structural-energy law of the physical theory of strength (8.2) [3,6]. The characteristic form of the functions HIN (h) of nanohardness can be found in the experimental data on the properties of the nonhardness of silver and gold [10, 14]. At high values of energy density in nano-micro volumes of material, higher than the density of melting energy, regardless of the sign of stresses, we observe an analogy of the functions of subtle energy processes of irreversible shape change and destruction of solids. This result made it possible to make an assumption that in physical and mechanical processes different in their external form, there is a single mechanism of corpuscular-wave nature. This is a structural-energetic nano-microscopic process of irreversible transformations of the shape of the activated volume of the body, a

change in the ratio of volume and surface (parameter X_{sv}) and molar energy parameters of the body.

Thus, formulas (7), (10) link the structural-physical parameter of nano-micro hardness Dn and the physical structural-energy parameter of the strength of the material.

8. Discussion of the results.

Using the SET dependencies, a relationship was established between physical parameters and standard mechanical ultimate strength indices, plastic deformations, heat generation, the number of dislocations, and other characteristics of the original and damaged material.

Using the equations of the theory and the physical initial parameters of the material, you can calculate the strength and durability. In clause 3. an example of solving this problem, for a given load $\sigma(t)$ and a given constant temperature. To calculate the initial parameters of the material, $U_o, \gamma_o(0), Gr_o = 0.5E\gamma_o(0)$, (boundary conditions of the equation), the analysis of rheological functions $\sigma(t)$ and $\varepsilon(t)$ was used.

To develop an integrated engineering analytical physical method for calculating strength, durability, it is necessary to complete work on systematizing methods for assessing the structural and energy parameter of the material Gr. In this article, we examined a method based on nano-micro-kinetic indentation.

U_o -- the second parameter of the boundary conditions of the main equation (3), it takes into account to a greater extent the macro properties of the TMS, the features of the volume change, the specific indicator of the boundaries of the activated region, etc. We have several ways to determine the activation energy of destruction U_o, this is the topic of the next article.

At present, many specialists have developed methods for analyzing the data of the force diagram of the kinetic indentation of the material, which allow, with sufficient accuracy for engineering calculations, to determine the stresses acting in the structural elements. The principles of this method can be seen, for example, in [17, 18]. By combining these studies and the SET methods, based on the indentation data, a promising direction for the complex application of physical methods opens up. Based on the results of a comprehensive analysis of kinetic indentation, it is possible to quickly and efficiently simultaneously investigate stresses, parameters of hardness, strength, durability, material damage, directly in the elements of existing structures of unique structures, etc.

Analytical methods for determining physical hardness from kinetic indentation data allow one to estimate the actual value of the structural-physical parameter Dn, acquired in the process of accumulation of damage by the material (plastic deformations, etc.). We propose methods that will analytically construct a diagram of the initial "zero" process, in the absence of a stress field. Thus, the physical method for analyzing nano-micro indentation data allows performing the operation of calibrating and adjusting the program and the algorithm for processing the data of kinetic nano-micro indentation. Analytically it is possible to obtain an indentation diagram of a "zero" process for a material damaged by loads in a structure. Thus, we can analytically correct the data of the indentation process, take into account the acting stresses in the material and irreversible changes in the material of the structural element.

Our studies have shown that the parameters and properties of the experimental force diagram obtained by the scratching method can be successfully analyzed by the physical method and the hardness criterion. The value of the physical differential hardness of the material according to the data of nano-microkinetic indentation and the value obtained by the scratching method meet the similarity criterion. The value of the physical differential hardness of the material obtained by the kinetic indentation method differs by a constant factor from the physical hardness obtained by the scratching method. This important theoretical result requires experimental verification.

The difference and advantages of the physical method. Molar physical CW parameters of the state of a material as TMS allow considering the influence of various physical, chemical, electrical, radiation and other factors affecting not only mechanical strength and durability, but the ability to maintain (lose) the initial parameters of chemical, technological and other quality and character. Molar physical characteristics can reflect the process of change in physical, thermal, chemical, electrical, etc. strength and durability. A positive property of the physical structural-energy theory is that practically any physical properties of a material and factors of influence (load) on it can be quantitatively estimated and comparable through CW molar parameters, through their corpuscular vortex, wave, energy properties. The molar energy characteristics of external factors and internal states are comparable and interrelated. A particular example of the use of such a physical relationship is spectroscopy in materials science, acoustic methods for monitoring microscopic destruction of material in mechanics.

Rheological changes (in time) of the material properties of interest to us under the influence of physical and chemical, technological and other factors can be investigated by the corresponding rheological equations of the physical theory of strength. This is possible, since there is a correlation of molar parameters with physicochemical and other properties of the material. For example, in [19], a relationship was established between molar parameters U_o, γ_o, heat capacity, coefficient of linear expansion, density, etc. The study of a new direction in the physical theory of solid strength is promising, especially in the development of nanotechnologies, for theoretical prediction of the strength properties of new materials, preliminary assessment of predicted limiting parameters in various combined operating conditions. The physical approach significantly expands the possibilities of calculating the strength and durability of a material under non-stationary operating conditions.

Preliminary studies of the physical principles of the influence of the hydrogen factor on the strength of rock salt, in different concentrations of salt solutions in water, according to the results of the experimental work of Ioffe [20], gave positive results. Using the molar parameters of rock salt and solutions, the influence of hydrogen ions on the ultimate strength of the rock salt crystal in solutions of different concentrations was taken into account analytically. Theoretically, the effect of hydrogen on the parameter of the activation energy of destruction was taken into account. These results confirmed our assumptions, the physical dependences of the theory allow us to estimate the influence of additional physicochemical factors on the strength of the crystal.

An integrated physical method for studying the hardness and strength of a material makes it possible to exclude a number of intermediate labor-intensive and costly processes associated with the determination of mechanical empirical indicators and parameters of material strength. An example is considered in [7].

9. Conclusions.

A theoretical basis has been prepared for creating algorithms and a program for determining the universal parameters of the physical hardness of a material based on the data of the standard kinetic indentation process. Data can be obtained by various methods and an indenter. The fundamentals of analytical methods for determining the parameters of the equation of kinetic hardness, molar physical structural-energy parameters of strength and durability of structural materials have been developed.

The results obtained suggest further development of the theory and verification of the obtained dependencies and methods together with specialists from various fields.

I propose to interested organizations to create a joint group of specialists in various scientific fields (strength, materials science, physics, chemistry, mathematics), for further joint theoretical and experimental work and the application of physical methods in studies of hardness, strength, fracture mechanics of materials, practical use of the results and preparation engineers of a new direction.

Acknowledgments

The author thanks Vasily Moshenka, Professor KHNAHU, for providing a large experimental material, his monograph on indentation and consultation.

Figure

Fig.1. The dependence of the amplitude of the magnitude of the cyclic tensile stress A_0 on the number of cycles to the destruction of the material N_*. 1. Frequencies 3, 70, 500 Hz. Temperature: 293 (20), 323 (50), 343 (70), Celsius temperature in brackets. Form of uniaxial tension cycle stress: $\sigma(t) = \sigma_0(1.001 - \cos B_s t)$. Material steel 45.

Fig. 2. Comparison of the nature of the functions: a) energy density function $PVA_0(h)$, differential hardness $PH_0(h)$, indentation by a sphere D5mm, Vickers pyramid, Test unit HB103, b) Berkovich pyramid, Test unit HB100, $PVA_V(h)$, $PH_V(h)$ Constructed according to the results of processing the functions F (h), data [11].

Fig. 3. Analytical modeling of physical functions of nano-micro indentation HIN (h) using equation (5). Diagrams of indentation of three hardness measures HB100 / 400/660, indenter is a Vickers pyramid, parameters Dn, PH = PHV, B = 0, method of addition of functions of nano-micro and macro processes are given.

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Fig. 5. The model of the formation of a nano-activated volume of material, the **leading process** of structural and energy transformations by a sharp indenter, the Berkoich pyramid: a- the initial stage to a depth of ho; b - formation of an activated $\mathbf{V_{LP}}$ **leading process** area; c - translation of LP activation with high energy density, formation of the total volume $\mathbf{V_{\Sigma NA}}$; The blue arrows show the LP energy dissipation.

Fig. 6. Graphic display of the structural-energy law for different thermomechanical systems: A - the law of state of an ideal gas, isotherms, constant mass; B - the law of the structural-energy state of a deformed solid (isochronous - isotherms). C - physical equation of nano-micro indentation. D - approximation by equation (5) of the experimentaldependence of the true ultimate strength of a pure gold $\sigma_*(h_v)$ nano layer on its thickness hv [16].

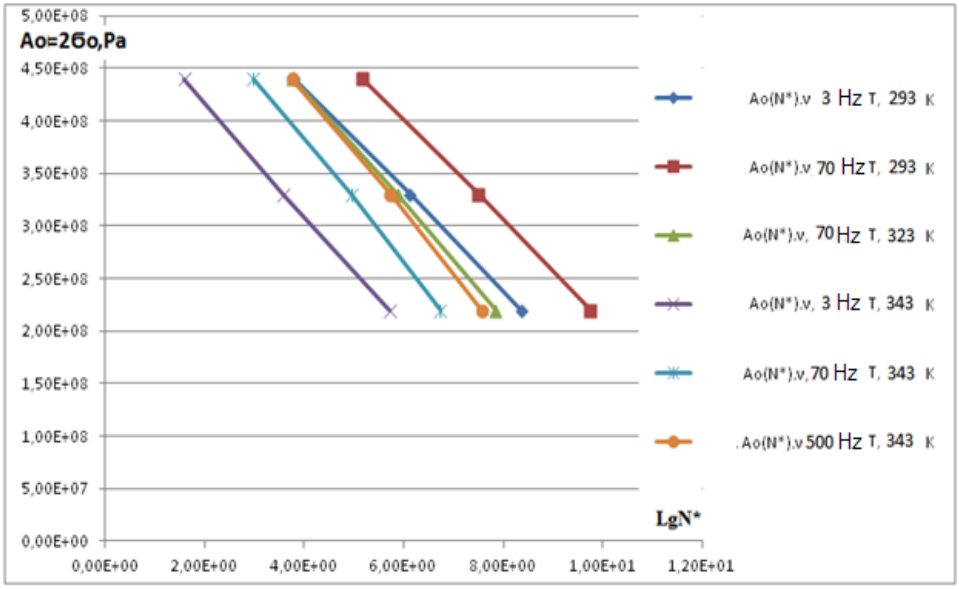
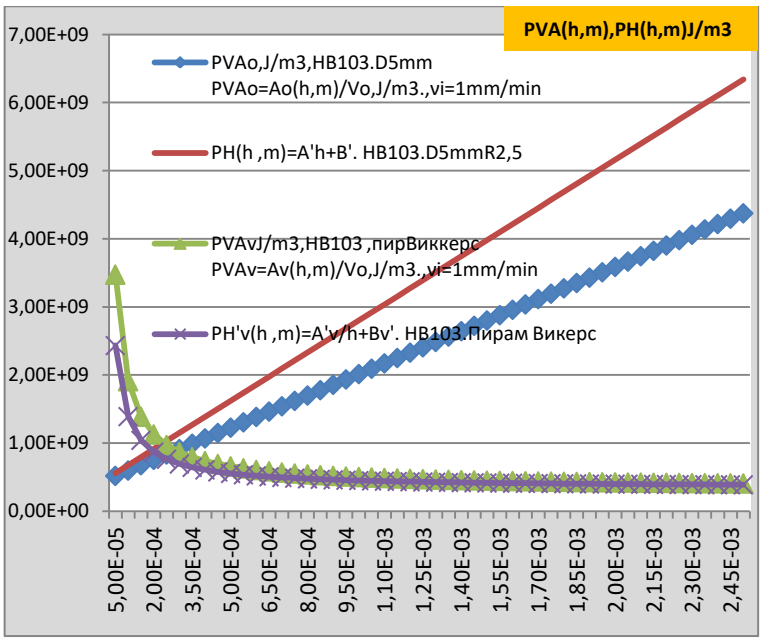


Fig.1. The dependence of the amplitude of the magnitude of the cyclic tensile stress A_0 on the number of cycles to the destruction of the material N_*. 1. Frequencies 3, 70, 500 Hz. Temperature: 293 (20), 323 (50), 343 (70), Celsius temperature in brackets. Form of uniaxial tension cycle stress: $\sigma(t) = \sigma_0(1.001 - \cos B_s t)$. Material steel 45.



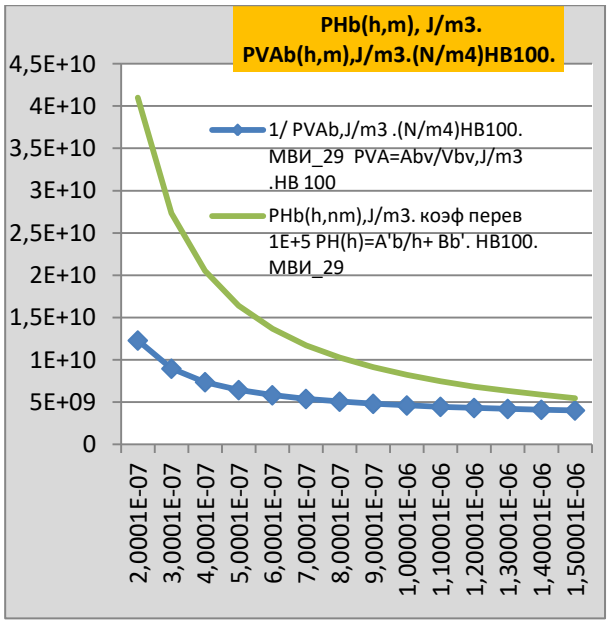


Fig. 2. Comparison of the nature of the functions: a) energy density function $PVA_o(h)$, differential hardness $PH_o(h)$, indentation by a sphere D5mm, Vickers pyramid, Test unit HB103, b) Berkovich pyramid, Test unit HB100, $PVA_v(h)$, $PH_V(h)$ Constructed according to the results of processing the functions F (h), data [11].

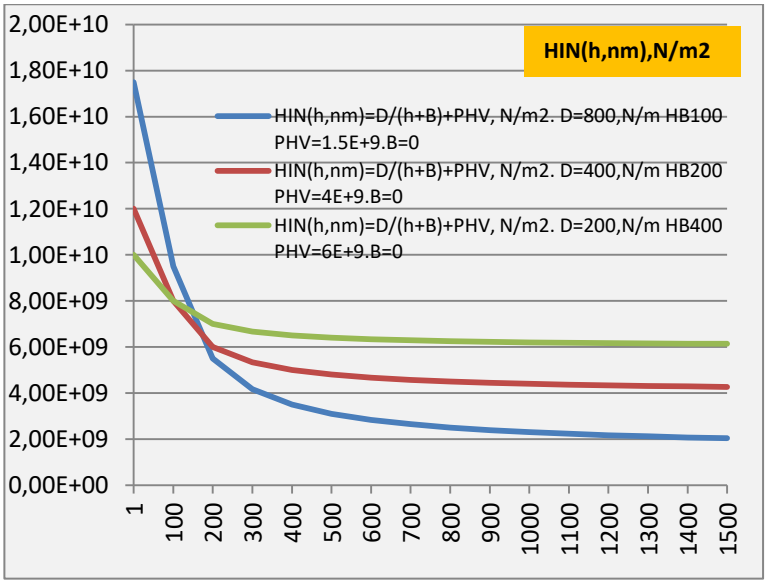
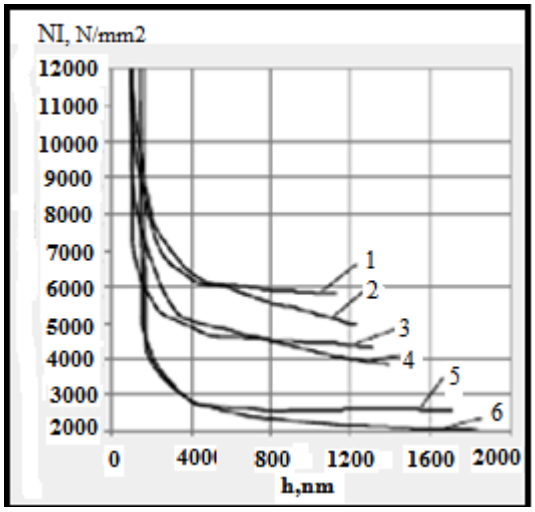
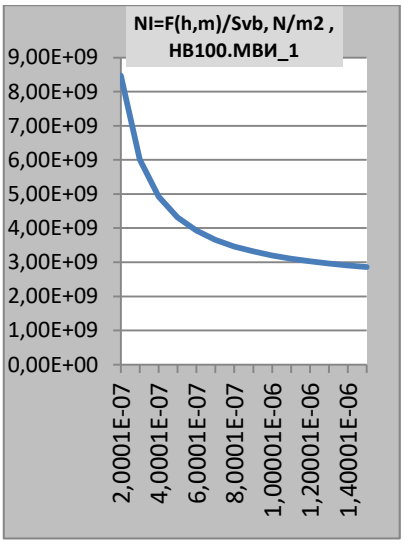


Fig. 3. Analytical modeling of physical functions of nano-micro indentation HIN (h) using equation (5). Diagrams of indentation of three hardness measures HB100 / 400/660, indenter is a Vickers pyramid, parameters Dn, PH = PHV, B = 0, method of addition of functions of nano-micro and macro processes are given.

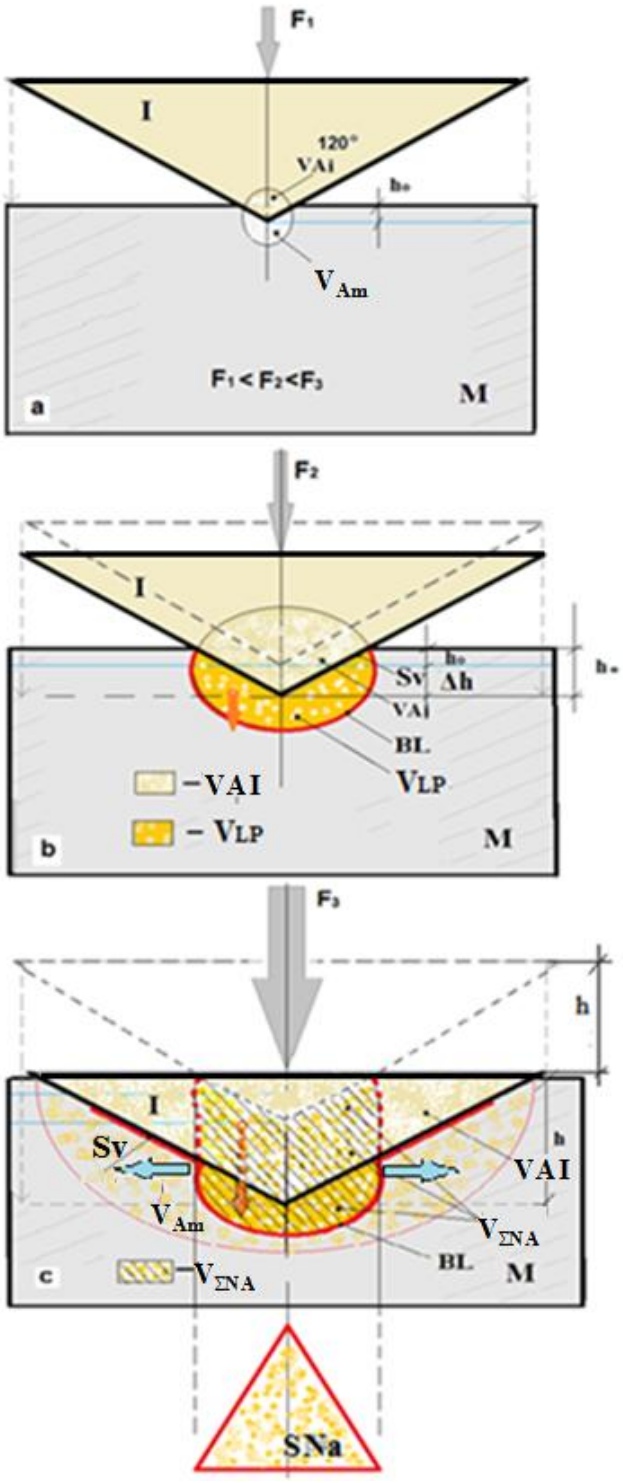


a)



b)

Fig. 4. Surface kinetic nanohardness NI (h) of steel samples: a) 1 - 788HV, 2 - 508HV, 3 - 73.2 HRA, 4 - 411HB, 5 - 28.9HRc, 6 - 103HB [12]. b) diagram **NI(h)= F / 27h**^{2} Berkovich pyramid, an exemplary measure HB103, built using the approximation of the experimental function F (h) [11].



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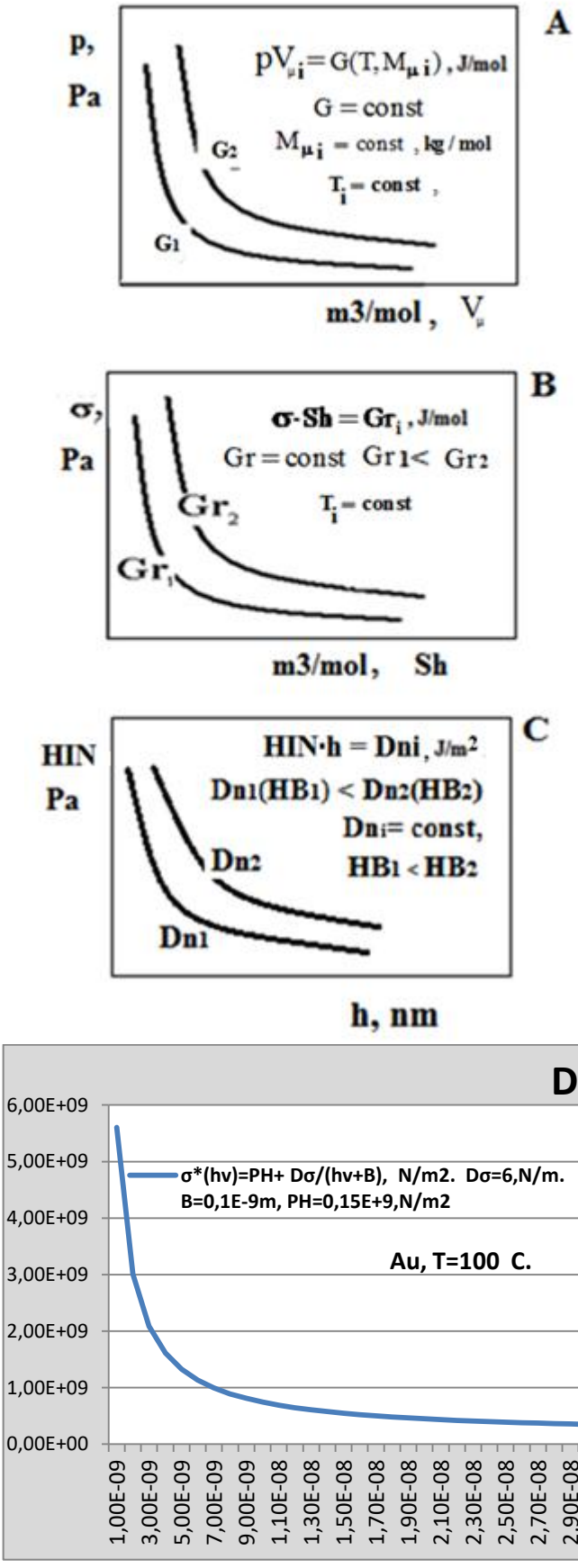

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