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Physical hardness of kinetic macroindentation of materials, theory and methods of determination, relationship with standard hardness. Application prospects.

Shtyrov Nikolay

Private Research and production Company "LYU". Nikolayev, Ukraine

Abstract

The physical properties of force diagrams of kinetic macroindentation of materials by the Brinell sphere are studied. Theoretical and experimental substantiation of physical concepts of the function and number of hardness, new analytical methods for analyzing data from the process of kinetic macroindentation. Universal physical unit of material macrohardness. Method for determining the function and number of physical macrohardness of the kinetic indentation of the material. The reason for the size effect in standard empirical methods for determining hardness is shown. A correct physical method for comparing and translating the hardness values of different scales is proposed. To analyze the force diagrams obtained by different indenters, to determine the correct values of the physical and empirical hardness of macroindentation, physical algorithms and formulas have been developed. The prospect of using the research results for different ranges of kinetic indentation, improving the ISO 14577 standard is discussed. An example of using the physical parameters of hardness in universal methods for calculating the parameters of strength, fatigue and durability of materials.

Key words: physical macrohardness of material kinetic indentation, theory, method, function, number, universal unit, application.

Modern indentation is a widespread multifaceted operational method for assessing the hardness, nano-microstructural and physical-mechanical properties of materials and thin coatings. The existing indentation methods can be conditionally divided into three historically formed areas:

1. Single act macro surface empirical indentation.
2. Macro instrumented kinetic indentation.
3. Nano-micro kinetic indentation.

Currently, there are a number of scales, standards and methods that do not have a reasonable systematization, there is no single universal way to correctly compare the hardness of a material obtained by different measurement methods. In practice, the following canonical definition has been fixed. **Hardness** is the ability of a material to resist a change in shape and the formation of a new surface when a tool made of a harder material is pressed into it (abbreviated) [1]. Let us briefly call this widespread experimental and analytical approach to determining the macrohardness number of a material using various tools the **empirical one-act hardness**, abbreviated **EH** (Empirical Hardness). By this designation we mean the methods of one-stage macro-surface empirical indentation. Instrumental kinetic indentation is considered separately. The generally accepted characteristics in EH indentation methods are: force F, indenter displacement h, conditional indentation area S (calculation formula depends on the method), etc. There is no physically and theoretically substantiated definition of hardness in EH [1,2,3]. The hardness values obtained by EH methods do not have a clear physical content and are not correctly comparable. The foregoing refers to the methods of scratching [3]. Studies have shown that the number EH of hardness, regardless of the method, is, in essence, the ratio of some given force F on the indenter to some conditional area S associated with the size of the contact surface of the tool and material, the calculation formula depends on the method. There are no physically correct principles for choosing S. Therefore, the value of EH can be considered as a conditional specific force, an incorrect value of pressure or compressive stress: EH = F/S, . The dimension of hardness is often not indicated, a dimensionless designation is used. We add that in the physical methods of analysis of thermodynamic mechanical systems, the magnitude of stress, pressure represent ambiguous characteristics of processes. The ambiguity of the EH hardness index is a consequence of the simplified representation of the complex thermomechanical system "indenter - material - mechanism". We designate this system as TMS (Thermomechanical System) [3]. Summing up, we can say that with the help of EH, some correlation parameters are determined by different methods and tools, which are historically called the hardness number of the material.

For solving particular applied problems of materials science, metallurgy, mechanics, etc., comparative methods of EH are acceptable. The construction of a general physical theory of kinetic indentation, the systematization and justification of the physical unit of hardness, the creation of a universal measurement standard and a single correct method for comparing hardness numbers obtained in different standards and ranges is an urgent task. Combining the standard of kinetic indentation and the standard for determining the mechanical characteristics of strength and fatigue on the basis of a general physical theory is a promising and relevant engineering and scientific and technical task.

Systematization, generalization, development of the EH standard and methods without a physical justification of these methods has no prospects. The construction of the theory of kinetic indentation and the justification of the physical unit of hardness, the creation of a base for a single measurement standard and the correct comparison of hardness numbers from different methods and ranges is impossible within the framework of the EH [1,2]. For the development and improvement of indentation methods, combining them with the theory of the strength of materials, it is necessary to create a basis - the physical theory of hardness. The article describes the first stage of building a physical theory of hardness of kinetic indentation.

Goal of the work. Form a physical model of the process of kinetic macro indentation of a solid material. Theoretically substantiate the physical concepts of the function of the state of the indentation process, the number and standard of the physical hardness of the material. Formulate similarity criteria and methods for comparing the macrohardness of materials. Show the ratio of physical and standard hardness. To reveal the reason for the size effect of macro indentation. Show the first results of the application and discuss the prospects for the development of new physical methods of kinetic indentation for the theoretical assessment of the strength and durability of structural materials using the methods of the physical theory of strength.

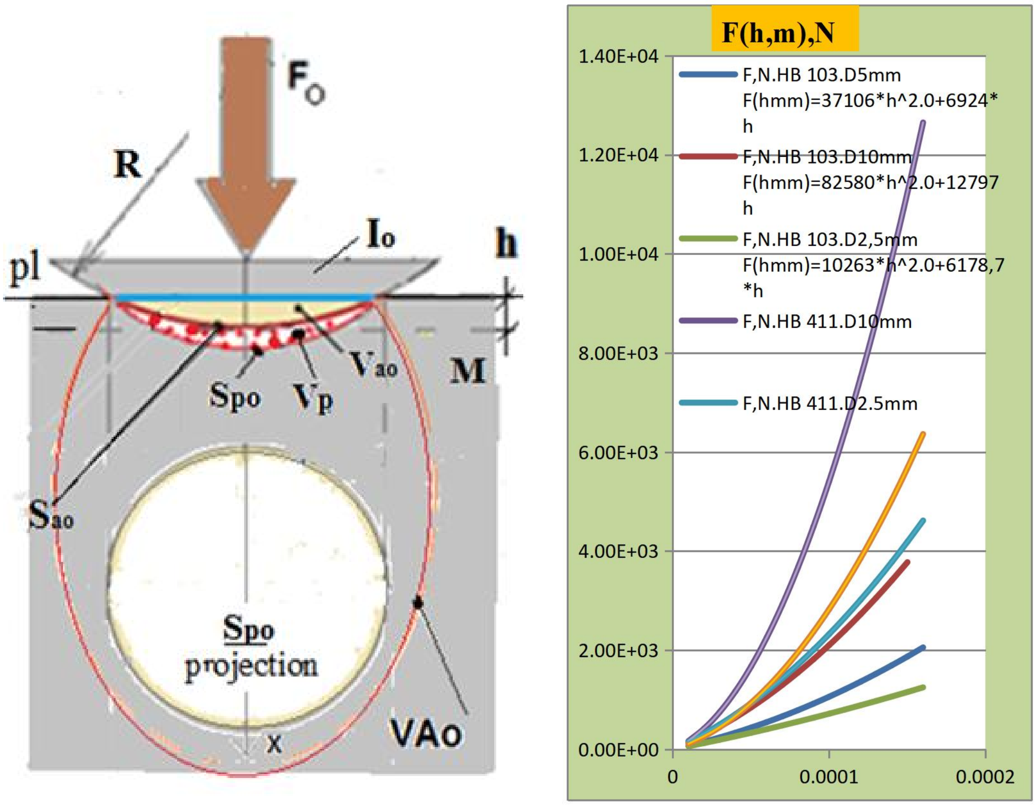
According to the results of the review, [2,3], the first physically correct determination of hardness using an indenter was the Calvert Johnson method (hereinafter briefly - MCJ), the article was published in 1858 [4]. The authors of MCJ formed the first generalized energy systematized dimensional scale of hardness values of different materials, subsequently they reworked it into a dimensionless one, etc. In order to maintain the similarity of testing materials of different hardness, physical principles were laid down in the MCJ. The indentation rate was low and approximately constant. The depth of indentation and the volume of extruded material during the tests were always the same. The mechanical work of the weight force of different loads acting on the indenter was measured at the same value of the displaced volume and the same indentation depth for different materials. The indenter had the shape of a truncated cone. In MCJ, the specific energy characteristic of the material and the generalized specific indentation power were measured experimentally, up to a certain constant factor. More details on the analysis of the method can be found in [3]. After forty years of constant application of the MCJ, technical improvements began that caused the violation and loss of the original physical principles. There was no theory of the hardness measurement process in MCJ. The original MCJ scale correct comparison of hardness was later supplemented with new data not systematically, without a theoretical physical justification. As a result, different empirical single-act methods for measuring the hardness number in different and not correctly consistent scales have emerged.

To create a physical theory and a universal method of kinetic indentation, I used a physical analysis of recognized experimental data of indentation according to the ISO 14577 standard [5], a physical structural-energy kinetic theory of strength and durability of materials [6,7]. The physical theory considers the processes of irreversible deformations and the destruction of a deformable solid body (deformable body - DB) using a physical corpuscular-wave model of volumetric associated interactions of structural units of solid bodies of any nature.

The physical theory of hardness considers the specific energy and rheological functions, parameters and properties of the kinetic process of material deformation during indentation tests. We use new concepts: the growth rate of the activated volume, the energy density of the activated volume (specific generalized indentation power), the function of the generalized force growth rate, the function of the activated volume shape change or the specific formed surface, etc. For an analytical description of the physical process of shape change during indentation, we obtain the state function process. To do this, consider the process of displacement, displacement, structural transformations of the material volume activated by the indenter. The following is a brief summary of the main points. More details on the method of analysis of kinetic macroindentation and measurement of physical hardness can be found in [2,3].

Scheme of the macro indentation process.

To create a physical model of the macro indentation process, consider Fig.1: scheme (a) and characteristic force diagrams (b). Diagrams of indetection by the Brinell sphere of exemplary hardness measures were obtained by Professor V.I. Moshchenok [1].



a b

Fig.1..a. Scheme of the process of forming the material macro indentation Brinell ball; b. - diagrams F(h,D), diameter $D\ 10\ /\ 5\ /\ 2.5\ \mathrm{mm}$, standard hardness measures HB103, HB411, experimental data [1].

Designations: M – material; Io - spherical Brinell indenter, further subscript o denotes a sphere. F_0- force on the indenter; VA is the conditional activated volume, in which reversible (elastic stresses) and irreversible deformation processes are simultaneously present; D - is the diameter, R - is the radius of the sphere. The volume boundary is shown conditionally as a red line. The upper boundary VA is the contact surface of the material sample. Activated volume Va(h) - the volume of the immersed body Io beyond the plane pl into the material. Physical activated volume -Vp. It is formed from the initial material M as a result of its compression, displacement, shaping, irreversible structural and energy transformations, under the action of force F. This is the volume in which the main irreversible structural and energy transformations of the material occurred during indentation. h is the displacement of the indenter. The volume Vp is limited by the surfaces Sa and Sp. The material in Vp is in an activated quasi-liquid state. S_{ao} - the surface of the activated material created, generated by the indenter. Sp - conditional outer boundary Vp. We assume that the area of the contact surface of the material and the submerged part of the indenter are equal. pl - material surface plane M. Contact surface projections: Spo, Spv. We assume Vao(h) = Vp(h).

Physical model of thermomechanical indentation system.

Figure 2 shows the elements of the physical energy model of the kinetic process of shaping and growth of the activated physical volume $V_p(h)$ of a solid body for macro indentation by a sphere. Parameters of the initial state of the material:

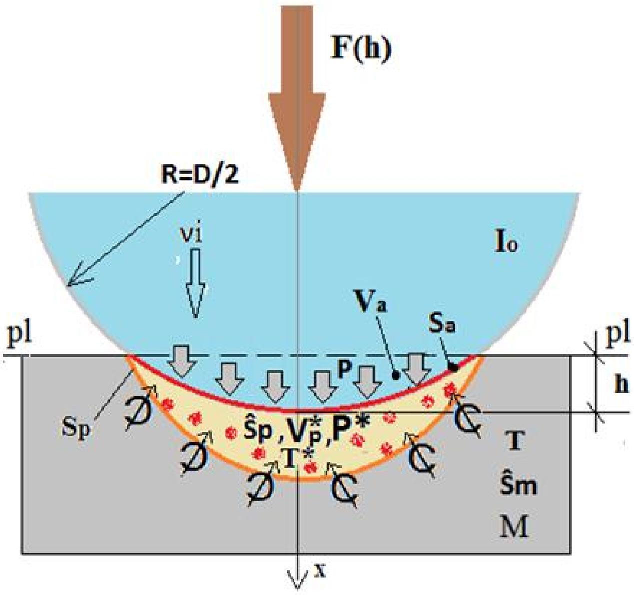


Fig.2 Physical model of the activated material volume V_p^* as a thermomechanical system.

T – temperature, P – conditional pressure, $\widehat{S}_m$ – entropy. When the indenter moves at a certain low speed $\upsilon_i = dh / dt$, a quasi-equilibrium process of continuous energy exchange of waves-vortices-quasiparticles occurs between all elements of the system. We assume that during the movement of the indenter, the activated volume Vp is continuously formed and grows with new intrinsic high parameters of the quasi-equilibrium state of the material. We assume that the change in the state of the initial structure of the material is completely characterized by new values of the state parameters in the volume $V_p(h)$. All parameter changes occur in some thin layer of the surface Sp (boundary region, yellow). We assume that the preparatory stage of relaxation, the formation of a stable process of transformations in the boundary region, is completed under the condition h >> h_* , h_* - some small depth of relaxation. In Figure 2, the Sp region is marked with $\not{s}$. This is the physical boundary (boundary area-volume) of the structural-energy transformations of the material and the formation of the activated volume Vp. All irreversible processes of translational-rotational transformations of the initial state of the material take place on the surface Sp, and the latent energy of the initial structure of the material is released. The volume $V_p(h)$ contains new physical parameters of the state of the material, they are marked with a superscript asterisk "*" and a subscript "p".

To describe the physical thermomechanical process of indentation, we use the concepts and terms of the monograph on thermodynamics [8] and the physical theory of the nature of internal forces in solids [9]. The authors of the research have shown, from the standpoint of statistical thermodynamics and quantum physics, that the stresses and pressures acting in a solid material body, arising under the action of some external factor or force, can be considered as work flows of impulses or energy quasi-particles in the volume DB, which form a macroscopic thermomechanical system. According to the physical theory of strength, external forces and other factors form, at the level of elementary structures, internal corpuscular-wave vortex flows of motion of the energy of quasiparticles. These torsion (vortex) energy flows of quasiparticles form fields of stresses and temperatures of the body, analytically their properties are displayed by the parameters of characteristic fluctuations, structural-energy function, molar potential DB, etc. [7]. We use the physical theory of strength to create a physical model and a function of the state of an activated (displaced, structurally transformed, etc.) material during indentation. Next, we formulate the energy physical criterion, the equation of state for the process of kinetic indentation of a material by a sphere, and define the concept of the number of physical hardness.

Physical thermomechanical potential, a function of the state of the activated volume of the indented material.

Consider $V_p(h)$ as a statistical thermodynamic system Fig.2 using the general provisions of thermodynamics, physical theory of strength and fracture of solids. Let us assume that all preparatory physical structural-energetic processes of material transformation take place in the physical boundary region S_p , outside the volume $V_p(h)$, in Fig. 2 it is denoted by the symbol $\varnothing$. Initial material parameters: $\widehat{S}$, P , T . In the physical boundary volume S_p of the surface, continuous structural-energy transformations of the material occur. A flow of energy enters S_p the volume $V_p(h)$ through the surface, as well as the translation of material particles with new physical parameters of the state. The volume $V_p(h)$ saves its own state parameters, indicated by an asterisk: $P \to P_p^*$, $T \to T_p^*$, $\widehat{S} \to \widehat{S}_p^*$. As a result, the activated volume $V_p(h)$ continuously increases. In this case, it is shaped and moved along with the indenter. Suppose we are given a state function $U(P_p^*, V_p^*, T_p^*, \widehat{S}_p^*)$ of a given activated volume $V_p(h)$ of material as a statistical thermodynamic system. From the physical theory [10], the potential of the internal energy of the system is:

$$U = Q - A, \quad J, \qquad (3)$$

Where, U - is the potential of the internal energy of the thermodynamic system. Q - heat energy transferred to the system. A is the work of external forces of the system.

$$A = \int PdV , \quad Q = \int Td\widehat{S}. \qquad T = const, \ P = const. \quad (4)$$

From (3) and (4), taking into account the accepted notation for the activated volume $V_p(h)$:

$$U_p = T_p^* \widehat{S}_p^* + P_p^* V_p^* , \qquad (5)$$

Where, $P_p^* = const, T_p^* = const, \ \widehat{S}_p^* = const.$

The volume V_p is continuously growing, while the parameters P_p^* , T_p^* , $\widehat{S}_p^*$, are constant. As a result of irreversible changes in the structure on the outer boundary surface S_p , an energy flux enters the volume $V_p(h)$. There is a change in the entropy of the original structure $\widehat{S}_p \to \widehat{S}_p^*$. This process is called the translation of a new structural-energy state into the activated volume of the material. The volume $V_p(h)$ increases, and the quasi-equilibrium state is preserved in it. Thus, the amount of matter, the total energy U_p and volume $V_p(h)$, are continuously growing. The energy in the activated volume comes from the external region, so the sign of the potential work A in (3) is changed to plus. Let us assume that the main part of the indentation work A is spent on an irreversible process and is dispersed in the volume $V_p(h)$. Thus, it can be assumed that the activated volume represents the equivalent thermomechanical system (TMS) of the kinetic process, in this case the thermomechanical potential of the activated volume is: $U_p = A(h) = A(V)$. By definition, a thermodynamic system must have a constant amount of matter. The amount of matter and the volume of our system are monotonously growing. Let's perform a conditional transition to a thermodynamic system with a constant volume and amount of matter, consider the properties of processes in a unit of the activated volume of the system, and determine the potential energy density U_p.

Potential of the generalized specific power of indentation.

Let us assume that during laminar kinetic macroindentation there is a physical thermomechanical potential of the activated volume $V_p^*(h)$, let it be equal to U_p . Assume that the potential represents a scalar field, a monotonic differentiable function of some parameters of this system. According to [11], the volume derivative of the potential U_p (6) is the limit of the ratio of the energy increment and the activated volume increment:

$$\frac{dU_p}{dV} = \frac{d(T_p^* \widehat{S}_p^* + P_p^* V_P^*)}{dV}, J/m^3 . \quad T^* = \text{const}, \; P^* = \text{const}. \qquad (6)$$

Let us denote the volume derivative of the macroindentation energy potential:

$$\text{PHMA}(V_p) = \frac{dU_p}{dV}, J/m^3 \qquad (6a)$$

Thus, we have determined the change in the energy density per unit of the activated volume of this system during kinetic macroindentation. The change in the density of the material is neglected. Depth h, volume V, and process rate vi are unambiguously interconnected quantities; therefore, the process time and indentation volume are one-to-one. Therefore, for (6a) we can use the term specific generalized power of the change in the energy potential per unit of the activated volume. Where, $\text{PHMA}(V_p)$ is the potential of the specific generalized power of macro indentation (6a). Imagine the volume V_p of the independent variable. Further, we assume $V_p = V_a$, for simplicity, we omit the subscript: $V_p = V_a = V$. As a result, we have obtained (6a) the generalized isochoric - isobaric - isothermal thermodynamic potential of the specific generalized power (per unit volume) of the activated volume of a solid as a result of CI. According to condition (5), the entropy and temperature of the increasing volume V is constant: $\widehat{S}_p^*$ = const, T^*= const, therefore $\partial U_p(T_p^* \widehat{S}_p^*) = 0$ .Further, the index asterisk is not written. Let us assume that the entire mechanical work of the indenter A is spent on the processes of shape change and structural-energy transformations of the initial state of the material in the activated volume of the material - V. Using the physical model DB in the structural-energy theory of strength [7, 12], we represent the activated volume V as a scalar field energies of waves-vortices-quasiparticles, which, when interacting, form a macroscopic set of elementary nonequilibrium systems, which are presented analytically as periodic characteristic fluctuations of the energy of the associated interaction of quasiparticles. As a result, we obtain the thermomechanical potential of the vector field of the DTT activated volume:

$$U_p = A(V) = P_p V_p \text{ , J. Where, } V_p = V \qquad (6.1)$$

According to ISO 14577 [5], the work of the indent force F(h) when moving the material in the direction of the x-axis (assuming x=h) is equal to:

$$A(V) = A(h) = \int_0^{h_{max}} F(h)dh \text{ ,J.} \qquad (6.2)$$

$$A' = \partial A / \partial h = F(h) . \qquad (6.3)$$

$$U_p = A(h) = A(V) = \int_0^{h_{max}} F(h)dh \text{ , J.} \qquad (6.4)$$

Using (4), (6), (6.1), (6.4) we obtain the volumetric (spatial) derivative, we call it the function of the potential of the specific generalized power of macroindentation of the material:

$$PHMA\ (V) = \frac{dA(V)}{dV} \text{ , } J/m^3 \qquad (7)$$

The derivative (7) is a certain function; it characterizes the change in the energy density per unit of the activated volume and the generalized power of the indentation process.

In [13], based on a large amount of experimental research, it is proposed to consider the hardness of materials as the ratio $\frac{\Delta A(V)}{\Delta V}$, this formula is entirely consistent with the principles of the physical theory of hardness. In my works [2,3], a theoretical substantiation and generalization of this simplified formula is proposed, which confirms the physical method of analyzing the force diagram for measuring the hardness of a material during indentation.

Experimental properties of the potential function of the specific generalized indentation power.

Let us determine the potential PHMA (V) for several materials. For this we use the experimental diagrams F(h), an example of Fig. 2, obtained for standard hardness measures. Indenter sphere, diameters $D10/5/2.5mm$, hardness measures HB103, HB176, HB411, experimental data [1].

For a sphere and a pyramid, we approximate the function F(h) by a polynomial (8), [1]:

$$F(h) = ah^{m} + bh^{m-1} + c \qquad (8)$$

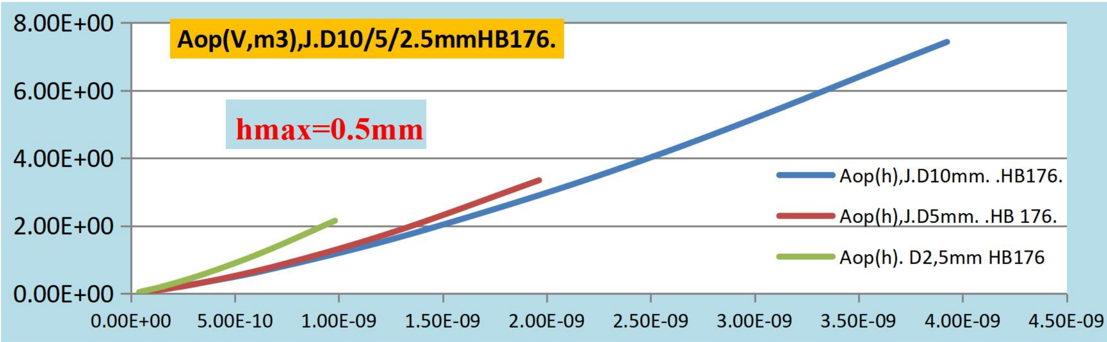
Where, a, b, c, m are approximation constants F(h) . In [1], the values of the necessary parameters were obtained: m = 2, parameters $a = a_o$, $b = b_o$, $c_0 \approx 0$, for a Brinell macrosphere of various diameters, for three materials of different hardness (standard measures). For the ideal case of indentation of standard measures, the laminar process [2,3], $c_0 \approx 0$. Using (6.2) and these parameters for (8), we construct the functions of the physical thermomechanical potential $A(V, m^3)$. A typical example of a function for HB176 Fig. 3a. Let's find the approximation equations for the function $A(V, m^3)$, for a linear trend, using the Excel-2007 method, example Fig.2b. The linear trend of the function $A(V, m^3)$ on the diagrams is shown by the equation $y = A'_v x$, the black line is the trend parameter. Based on the analysis of the experimental data, for different diameters of the sphere and three measures of hardness Table 1, formula (9) was obtained, for laminar macro indentation by the sphere, the values of the trend parameter were obtained $A'(V)_v$:

$$PHM\ (HB) = PHM = A'(V)_v = \frac{\Delta A}{\Delta V} \approx \frac{dA}{dV} = const, \ J/m^3 \qquad (9)$$

Where, $A'(V)_v$ the linear trend parameter of the function $A(V)$.

Let's establish the term for the derivative $A'(V)_v = PHM$ **- the value (number, parameter) of the physical macrohardness potential of the kinetic laminar indentation of the**

material. For a homogeneous stable isotropic material, an integral quantitative physical characteristic of the change in the structural-energy properties of the material during laminar kinetic macroindentation with a Brinell sphere is obtained - the **potential of physical macrohardness.**



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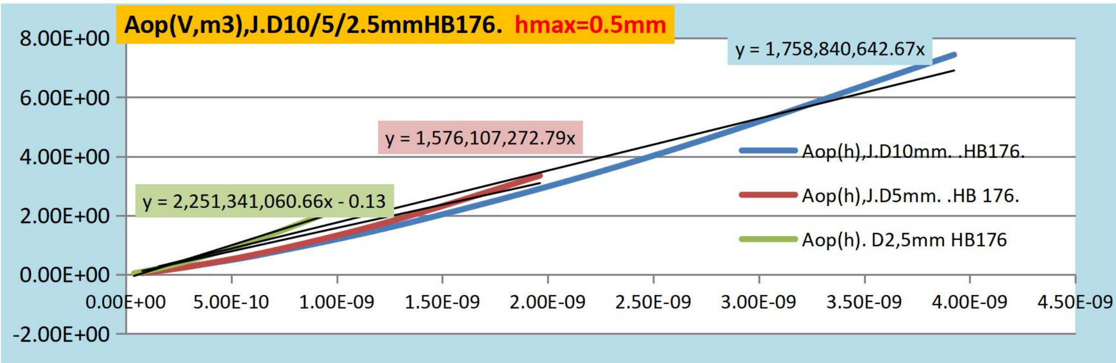

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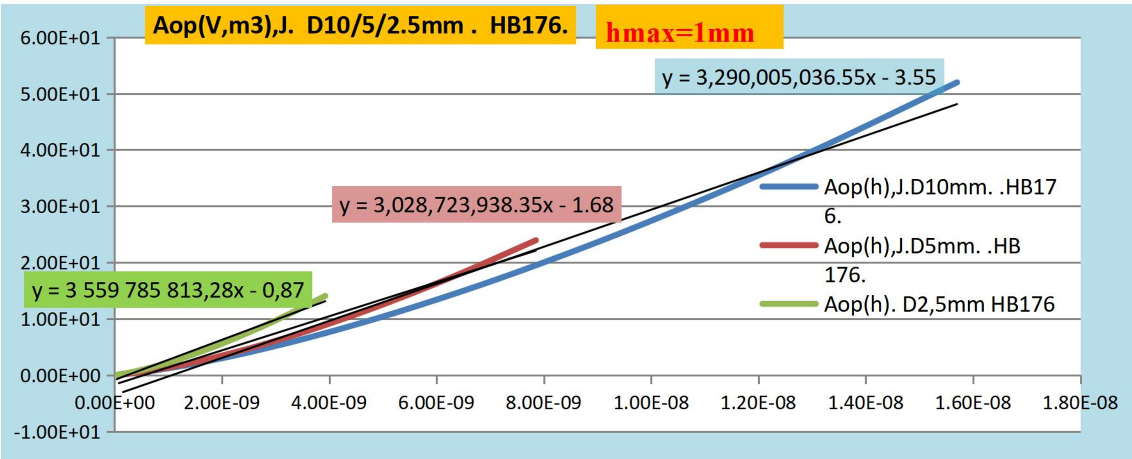

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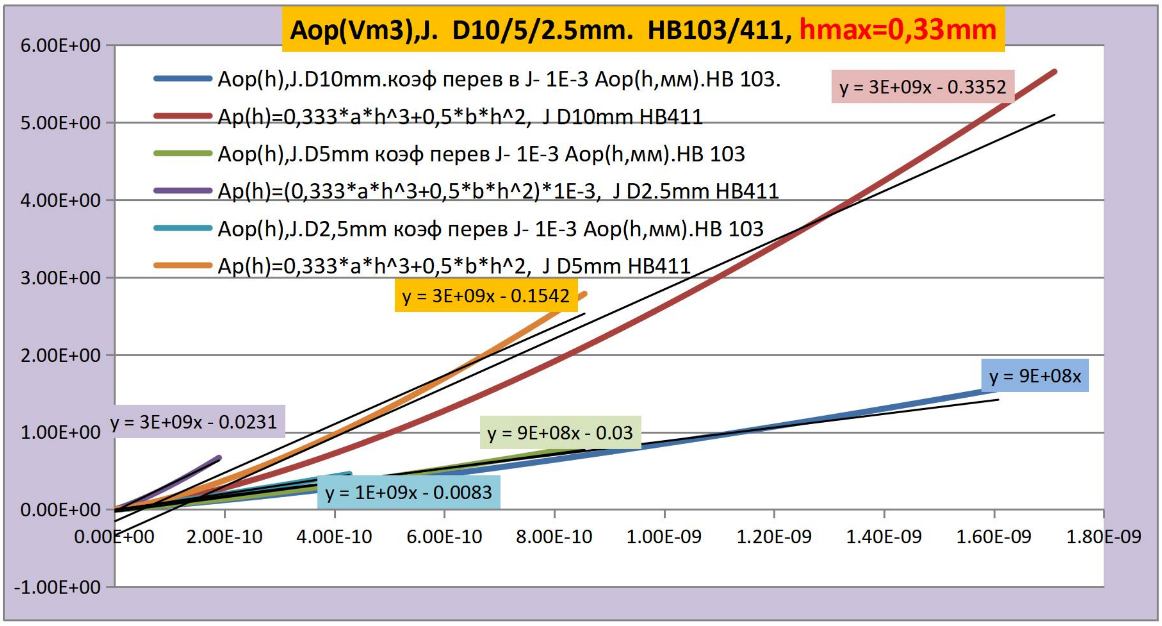


d.

Fig. 3: a) Approximation of the potential function macro indentation $A(V, m^3), J$, standard hardness block HB176, indenter D10/5/2.5mm. b) Linear trend (black) of each function, HB176, trend equations $y = A'(V)_v \cdot x$ c) h max = 1.0 mm. d) HB 103/411, h max = 0.33 mm. Diagrams F(h) V.I. Moshenok [1].

Table 1 shows the results of my calculation of the physical macrohardness potential of kinetic indentation with a Brinell sphere, diameter 2.5/5.0/10.0 mm. Experimental diagrams F(h), data of prof. V.I.Moshchenko KHNADU [1]. Used for testing exemplary measures of standard hardness HB103/176/411.

From properties (7), (9), analysis of experimental data Table 1 and Fig. 3, it follows that the thermomechanical potential $A(V)$, on a certain interval $h_{PH\min} < h_{PH} < h_{PH\max}$ can be represented as a linear function with respect to volume V_a:

$$A(V) = PHM(HB) \cdot V_a = A'(V)_v \cdot V_a \text{ , J ,} \qquad (10)$$

Where , $A'(V)_v = PHM = const$, J/m^3

From the analysis of Table 1, we see that the main parameter of the physical macrohardness potential is approximately equal, sometimes coincides, with the value of the empirical hardness

Table 1. Physical potential of macrohardness of kinetic indentation with a Brinell sphere, material - exemplary measures of standard hardness HB103/176/411.

standard measure of hardness $HB \cdot 10^7, N/m^2$	**Average parameter value physical hardness potential** $J/m^3 (N/m^2)$	$PHM = A'(V)_v$, $J/m3$ **Physical hardness potential parameter of indentation, hardness test blocks HB103/411, hmax=0.33mm, HB176, hmax=0.5mm, D 10.0/5.0/2.5,mm**		
HB 411	$330 \cdot 10^7$	$3{,}5 \cdot 10^9$, (D2,5)	$3{,}1 \cdot 10^9$, (D5)	$3{,}2 \cdot 10^9$, (D10)
HB 176	$185 \cdot 10^7$	$2{,}23 \cdot 10^9$, (D2,5)	$1{,}58 \cdot 10^9$, (D5)	$1.76 \cdot 10^9$, (D10)
HB 103	$94 \cdot 10^7$	$1.0 \cdot 10^9$, (D2,5)	$0.94 \cdot 10^9$, (D5)	$0.89 \cdot 10^9$, (D10)

HB obtained for the corresponding standard measure (coincidence is marked in green). It has been established that with an increase in the hardness of HB, depth h_{PHmax} and volume V_{max}, the discrepancy between the physical and empirical hardness increases. Note that with an increase in the diameter of the indenter D, the absolute value of the maximum activated volume always increases $V_{max} = V(h_{PH\,max})$, where $h_{PH\,max}$ is the maximum depth for this test. Next, we will discuss the reasons for the increase in the physical potential of the tested hardness measure in relation to the number of empirical standard hardness HB.

Analysis of the properties of the thermomechanical potential of indentation by a sphere.

From (6.1) it follows that the thermomechanical energy $A(V)$ potential of the activated volume V is equal to $A(V)=U_p$. Using the physical model [2], we represent the potential as a scalar field of the physical parameters of the activated volume V.

According to the general field theory [14], the volume derivative (7), the function of the potential of the scalar field of the energy density, as well as the specific generalized indentation power is equal to the energy density gradient:

$$PHMA(V) = \frac{dA(V)}{dV} = gradA = \frac{\partial A}{\partial V_x} + \frac{\partial A}{\partial V_y} + \frac{\partial A}{\partial V_z} = PHI_x(h) + 2PHI_z(h)\ J/m^3 \quad (11)$$

Where, $gradA$ is the gradient vector of the potential $A(V)$ on the surface of the volume $V(h)$.

$PHI_x(h) = \frac{\partial A}{\partial V_x}$, $PHI_y(h) = \frac{\partial A}{\partial V_y}$, $PHI_z(h) = \frac{\partial A}{\partial V_z}$ - components of the potential gradient along the coordinate axes

$PHI_x(h) = \frac{\partial A}{\partial V_x}$, $PHI_y(h) = \frac{\partial A}{\partial V_y}$, $PHI_z(h) = \frac{\partial A}{\partial V_z}$ - are components of the potential gradient along the coordinate axes. For a sphere (subscript - o), suppose $PHI_{yo}(h) = PHI_{zo}(h)$. . The potential $PHMA(V)$ of macro indentation by a sphere is the gradient vector of the scalar field of the energy density of the activated volume on the surface S_a . $PHMA(V)$ can also be represented as a function of the generalized rate of specific energy flow on the surface of the activated volume. Gradient (11) is the total specific generalized power of energy flows through the entire outer surface (Fig. 2) of the activated volume $A_a = V_{ph} = V$. In the process of CI, energy flows (flows of work of waves-quasiparticles) arise; they can be represented by three components along the coordinate axes [3]. The shape of the indenter body (sphere, pyramid, etc.) affects the value of each component of the total hardness potential. Each component is a part of the total potential energy flow $PHMA(V)$ (11). For a sphere, for a homogeneous isotropic material, the two components of the Z, Y axes are the same in absolute value. This means that the potential $PHMA$ or physical hardness depends on the homogeneity and anisotropy of the material, the depth and shape of the indenter.

Let's denote $PHI_x(h, HB)$ - the main component of the gradient of the generalized power, the physical hardness of macro indentation in the direction of the coordinate h (Fig. 1; 2, or the X axis). Let's examine the main component of the gradient. Let us find the partial volume derivative , the direction of the X axis and the movement of the indenter coincide: h = X.

Using formulas (6.2), (6.3), we assume in the first approximation that for small depths $A_x \approx A$ we obtain:

$$PHI_x(h,HB) = \frac{\partial A_x}{\partial Vx} = \frac{\partial A}{V_P'(h)\partial h} = \frac{A'(h)\partial h}{V'(h)\partial h} = \frac{A'(h)}{V'(h)} = \frac{F(h)}{V_x'(h)}, N/m^2, \ A_x \approx A \quad (12.1)$$

Where, from (6.3) $A' = \partial A / \partial h = F(h)$, $\partial Vx / \partial h = V'(h)$. (12.2)

Using the approximation of the experimental functions , from [1], the values m=2, $c \approx 0$ for the polynomial (8), using (12.1), (12.2) we obtain:

$$PHI_x(h,HB) = \frac{\partial A_x}{\partial Vx} = \frac{F(h)}{V_x'(h)} = \frac{F(h)}{2\pi Rh} = \frac{F(h)}{S_{op}} = \frac{a_o h^2 + b_o h}{2\pi Rh}, J/m^3 \ (N/m^2), \quad (12.3)$$

Where, $V_x' = \partial V_x / \partial h = (\pi R h^2)' = 2\pi R h \cong S_{op}(h), V_{xo}(h) = \pi R h^2$ (12.4)

Where, $S_{op}(h)$ is the projection of the contact surface $S_{ao}(h) \cong 4\pi Rh$ onto the plane pl, Fig.1a.

From (12.3) follows two variants of formulas for the main component of physical hardness.

For laminar macroindentation by a ball of standard measures, from (12.3) we obtain [2]:

$$PHI_x(h,HB) = \frac{F(h)}{S_{op}(h)} = HI(h), N/m^2, \quad (12.5)$$

In the general case of laminar macro indentation by a sphere or pyramid, we have:

$$PHI_x(h,HB) = \frac{1}{2\pi R}(a_o h + b_o), \ N/m^2 \quad (12.6)$$

It follows from (12.5) that for the case of laminar macro иindentation (in this case, the displacement of the diagram F(h) along the axes is negligible $a_o h >> b_o$ [3]), the main component of the physical hardness gradient of kinetic macro indentation PHI_x represents the kernel of the empirical macro surface hardness function HI(h) . Let us expand the dimension (12.3): $J/m^3 = N \cdot m/m^3$ reducing by m, we obtain the dimension $HI(h), N/m^2$ (12.5).

From (11) it is obvious that the gradient of the specific indentation PHMA (V) power is the sum of three components along three coordinate axes. Note that the absolute value of the gradient PHMA (V), (11), is greater than the main component (12.1) $PHI_x(h,HB)$:

$$PHMA\ (V(h)) > PHI_x(h, HB) \quad (13)$$

Conclusion. The component $PHI_x(h,HB)$ is a linear function of the empirical macrohardness of the material , is part of the gradient or part of the function of the total specific power, the intensity of the physical flow of the work of waves-vortices of quasi-particles of energy, flowing through the entire physical, incl. and a contact surface enclosing the activated volume. Through the surface of the mechanical contact Sa along the axis h=x, a flow of variable power of the thermal mechanical energy of quasiparticle waves flows. From (12.6;12.5) it follows that for a spherical indenter, with an increase in the depth h, the value of the component $PHI_x(h,HB)$, the same as the empirical macrohardness HI(h) , grows monotonically linearly. In Fig.4a, the diagram of the main component $PHI_x(h,HB)$ of the laminar indentation of the reference measures HB176 and HB411, D2.5/5/10mm, the nature of the diagrams confirms this property. From a comparative analysis of the potential $PHM\ (h,HB)$ and the function $PHI_x(h,HB)$, it follows that their values differ by a factor. If the ratio of depths when measuring each of the indicated parameters is unchanged, then the multiplier is constan $k_{CHR} = const$ t:

$PHI_x(h,HB) = k_{CHR}$ PHM, Where k_{CHR} - choreic – rheological coefficient. (13.1)

If the process is ideal laminar $PHI_x(h,HB) = PHM$, $k_{CHR} = 1$.(13.2)

This property has been verified on experimental data for four steels. With full coincidence of the ranges of indentation by the sphere, $k_{CHR} = 1$ Table 1. Figure 4b together shows the experimental function of empirical hardness [2] and the function of the component , HB411 hardness measure, sphere D5mm. The functions of physical and empirical hardness, for one material (standard measure) coincided. In the empirical hardness formula (12.4), according to [1], the coefficient is used $\delta = 2$, while both formulas give the same hardness values. This experimental property is repeated for other hardness tests of macroindentation by a sphere, then the property was proved analytically [2, 3].

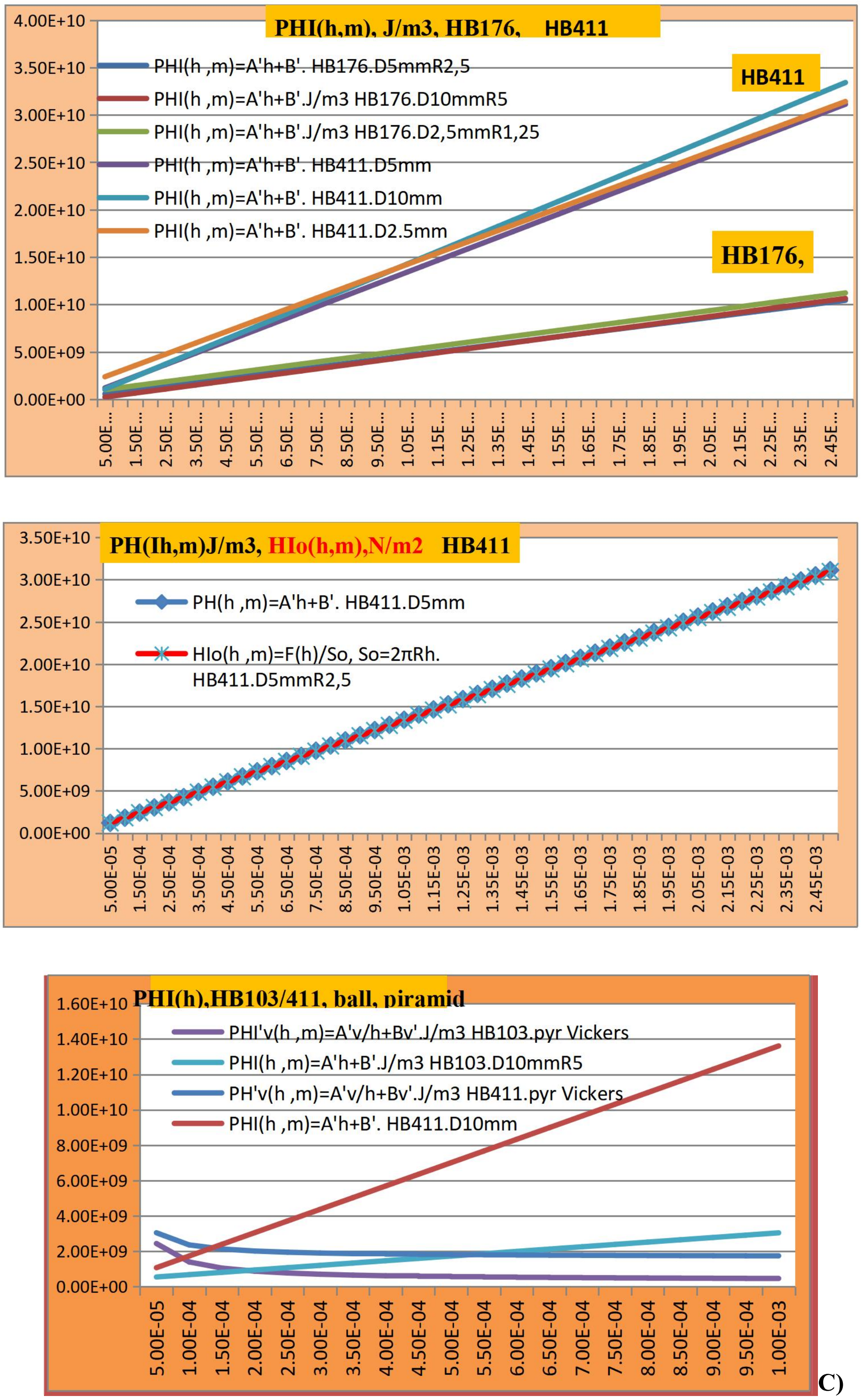


Fig 4 Hardness diagrams: a) the main component of physical macrohardness $PHI_x(h, HB, D_n)$, hardness test HB176, HB411, D10/5/2.5 mm, index x is not shown, according to [1]; b) together $HI(h)$ and $PHI(h)$, HB411, D5/2.5 mm; c) D10mm sphere and Vickers pyramid $PHI(h)$ diagra.

In Fig.4a, the functions PHI(h,HB) for different measures of hardness HB176/411 with different diameters of the sphere D2.5/5/10 mm. For the same measure of hardness, regardless of the diameter, the graphs of the functions almost coincided. For the same measure , but different diameters D, the functions of the empirical hardness $HI_o(h)$ and the component of the physical hardness $PHI(h, HB_i)$ gradient coincide, they are invariant to the diameter of the sphere, the slope of the straight line for diagrams of different diameters is the same.

On Fig. 4c we see the difference in the nature of the physical diagrams $PHI(h, HB_i)$ of the sphere and the Vickers pyramid, they are built according to the approximation F(h) [1]. At the pyramid, the process is not laminar and is displayed by another hardness function PHI [3].

Physical similarity of indentation processes, choice of macrohardness standard in the empirical method for determining the hardness number.

The physical analysis of the data of the indentation process performed on different hardness tests and a sphere of different diameters made it possible to formulate analytically the conditions for the unambiguous and correct determination of the empirical macrohardness number of the material. First of all, it is necessary to fulfill the conditions of similarity of physical testing processes. For laminar macro indentation with a sphere of various diameters ($D \geq \approx 2{,}5mm$), the similarity of the physical conditions for measuring hardness with a sphere is performed at a constant reference depth of indentation, regardless of the diameter of the macrosphere.

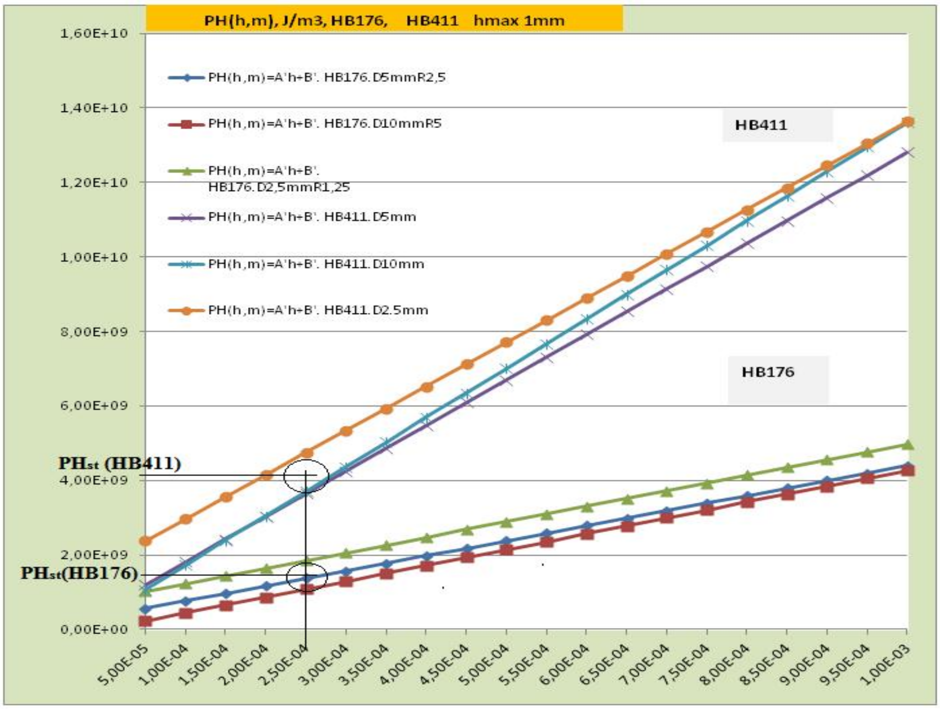


Fig.5 Determination of the standard of physical and empirical hardness, using experimental diagrams of physical hardness PHI (h), for standard measures HB176, HB 411, D=10.0/5.0/2.5mm:. The value PH_{st}, is approximately equal to the hardness of the standard HB measure. Reference depth $h_{st} = 0.25mm$.

It is necessary to approve the depth standard h_{st} of the method or measurement standard, then indent with a different sphere only to one depth h_{st}, Fig.5. It is known from the practice of hardness measurements [1] that the number of empirical hardness of a material on the Brinell scale depends on the indentation depth h, this property is called the size effect. It was shown in [2] that in the Brinell method, the correct value of the hardness standard number for different materials and different sphere diameters D must be found for a certain constant given depth h_{st}. Violation of this rule is the physical cause of the size effect. It was also shown in [3] that this similarity rule, taking into account the shape and size features, is valid for a pyramid, a cone, etc. For more details, the similarity conditions and criteria for comparing physical hardness for different shapes and sizes of an indenter (cone, micro tool) in [2,3].

Figure 5 shows the principle of determining the standard of macrohardness, the indenter is a sphere, the material is standard HB176/411 hardness measures. In Table 2, the results of calculating the number of physical hardness according to Brinell by formula (12.6), the values of the approximation parameters (8) for three different measures are the data [1]. The value of the conditional standard is accepted by the author only to check the properties of the method.

As a result of the calculations, it was found that for three different indenter diameters, provided that the measurement processes are similar and the hardness number is constant.

Figure 6 shows in a generalized form the sequence of determining the number of physical hardness PH_{Si} $i = 1,2,3$ according to the force diagrams Fi(h), fig.6a,b for three standard hardness measures HB_i and three different sphere diameters. Figure 6b shows three physical diagrams of macrohardness $PHI_i(h, HB_i)$ for a sphere, each beam corresponds to three initial functions F(h, D,HBi). Each line $PHI_i(h, HB_i)$ corresponds to one material hardness and three diagrams F(h) for three sphere diameters D (we have an invariant). The dotted line (black) shows the point of intersection with each ray of the abscissa h_S - the standard depth standard, this is how the value (ordinate) of the standard of physical hardness $PH_{Si}(h_S)$ of each material (measure) is determined. The yellow dotted line shows how the hardness values PHsi change during an uncontrolled transition to a new depth hSX . In this case, the physical conditions for the similarity of measuring the specific generalized power of the indentation process are violated, the depth, activated volume, and contact area change. An increase in the depth $h_s \rightarrow h_{sx}$ caused a distortion of the hardness scale.

The green color shows the theoretical hardness diagrams for the MCJ method, conditional soft $PH1_{MCJ}$ and hard materials $PH2_{MCJ}$ are shown, $PH1_{MCJ} < PH2_{MCJ}$, Calvert and Johnson truncated cone indenter [3,4]. The physical hardness, for a truncated cone MCJ, is slightly dependent on depth. This property was not directly used in the calculations, the authors used an indirect technique that provides similarity of physical conditions and an indirect method for determining the physical hardness number - they determined the weight of the load corresponding to a certain hardness of the material, h_{max} = const.

Table 2. Physical macrohardness of standard hardness tests, conditional standard h_{st}.

Reference test block HBW $HB \cdot 10^7, N/m^2$	**Average value of physical hardness** PH_{st} J/m^3	**The theoretical value of the standard of physical hardness from (9.4)** $PHI(h_{st}) = PH_{st}$, $J/m3$, $h_{st} = 0.25mm$ **D 2.5/5/10mm, HB411/176/103 hardness test**

HB 411	$403 \cdot 10^7$	$474 \cdot 10^7$, (D2,5)	$364 \cdot 10^7$, (D5)	$371 \cdot 10^7$ (D10)
HB 176	$145 \cdot 10^7$	$185 \cdot 10^7$, (D2,5)	$137 \cdot 10^7$, (D5)	$108 \cdot 10^7$ (D10)
HB 103	$105 \cdot 10^7$	$111 \cdot 10^7$, (D2,5)	$103 \cdot 10^7$, (D5)	$107 \cdot 10^7$ (D10)

In Table 2, an example of calculating the standard hardness PH_{st} for a conditional standard $h_{st} = 0.25mm$, equation (12.6) is used. When determining the standard method of hardness HBW, the depth h is not strictly regulated. For this reason, we cannot correctly obtain a stable coincidence of the values of physical and empirical hardness, since in empirical methods there is no control of the similarity of physical processes, in modern standard methods there is initially no criterion for the similarity of the physical conditions of indentation tests.

In the experimental work [15], the results of indenitation of different materials at a constant indentation depth are analyzed, the results obtained by the author confirm our theoretical calculations. The author's conclusion is that the size effect at a constant indentation depth is insignificant, it is necessary to measure the hardness at a constant indentation depth.

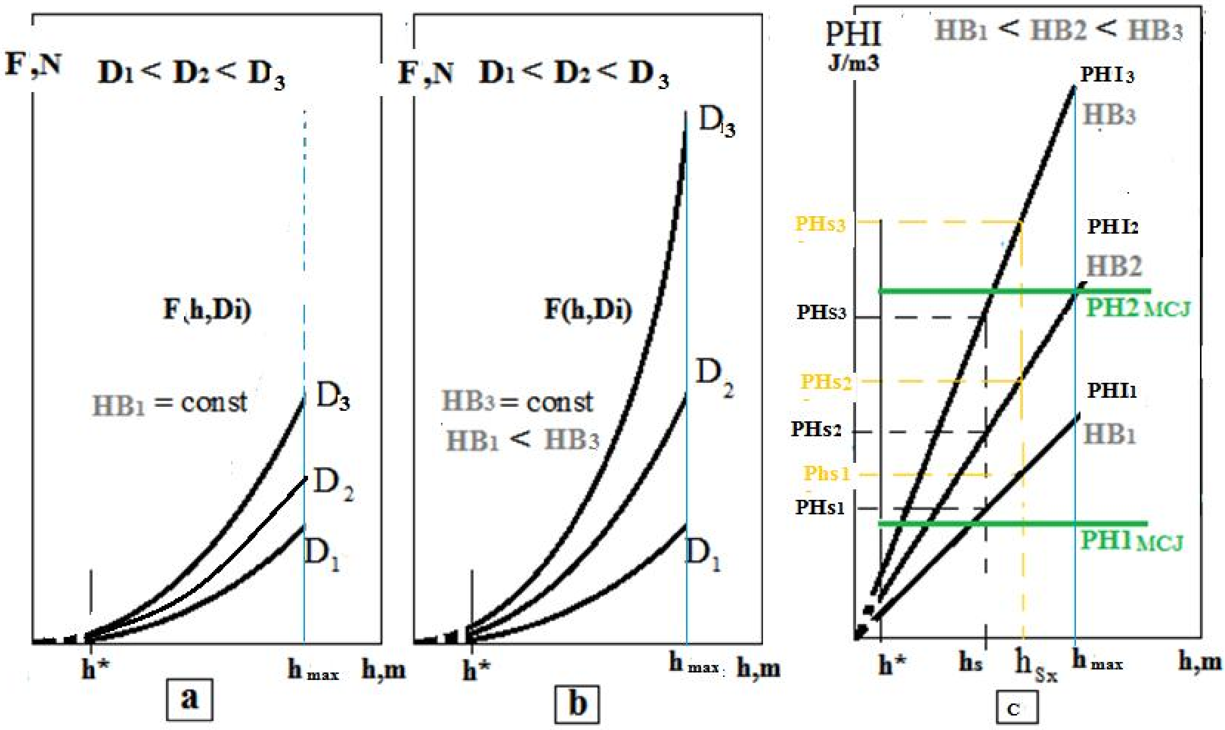


Fig.6 Generalized diagrams F(h) ,PHI(h) of macro indentation with Brinell ball and MCJ cone: a) Functions $F_n(h,D_n)$, for three diameters $D_1 < D_2 < D_3$,, hardness $HB_1 = const$; b) Functions $F_n(h,D_n)$, for three diameters $D_1 < D_2 < D_3$, hardness $HB_3 = const > HB_1$; C) Functions $PHI_i(h, HB_i)$ for three different values of HB1,2,3, each beam corresponds to one hardness function PHI(h) invariant D.

The reason for the deviation from the standard hardness number in empirical methods.

An analysis of the F(h) diagrams and hardness functions of kinetic indentation by a sphere (also pyramid, cone), materials of different hardness, showed that the absolute value and nature of the hardness function depend on the specific generalized power or energy flux of quasi-particle waves (work flow) passing through contact surface Sa. The total power of the energy flow of waves-quasiparticles during indentation (shaping) of the material melts together with the volume Va, the absolute number of periodically destroyed associated structural-energy bonds in the volume increases (the total number of characteristic fluctuations increases). As a result, the energy flux density of waves-quasiparticles of strength increases through the area of the contact surface of the activated volume [3]. The intensity of the energy flow of waves-quasiparticles through the area of the contact surface Sa (the work flow of pressure, stresses, heat) depends on the force F, the energy density of the activated volume (elastic energy and the energy of irreversibly broken bonds), on the value of the activated volume Va , the area of the contact surface. From the analysis of the hardness diagrams, it follows that the change in the shape of the indenter is analytically reflected in the value of the ratio Sa /Va. To analyze the physical reason for the influence of Sa /Va on the hardness number of indentation by a sphere, let us consider the ratio of two characteristics of the process: the relative dimensionless generalized growth rate of the contact surface projection area ν_{sp} and the generalized growth rate of the activated volume ν_v . Denote:

$$X_v(h) = \frac{\nu_{sp}}{\nu_v} = \frac{1}{h},\ 1/\text{m}. \quad (14)$$

Where, ,1/m. - the generalized speed of forming and at the same time the generalized speed of the translational motion of the indenter,

$$\nu_V = \frac{\partial V}{V \partial h} = V'_h / V\ ,\ \nu_s = \frac{\partial S_{ap}}{S_{ap} \partial h} = S'_{ap} / S_{ap}\quad Sap = 2\pi Rh \text{ - projection of Sa onto the plane pl.}$$

It follows from (14) that the dimensionless growth rate V of a sphere, regardless of its diameter, is higher than the growth rate of the contact surface. With an increase in h, the specific volume index of the contact $X_v(h)$ surface area continuously decreases, while the relative size of the contact - the cross section of the energy flow - decreases. For this reason, the specific energy flux - per unit area, flowing through the contact surface, increases with increasing h. The specific power of the energy flow increases - there is an increase in physical hardness. This is shown by the diagrams Fig.4,5. According to the definition of the physical hardness of a material and formula (12.3), an increase in the energy flux density (power density) during the formation of a new surface occurs with a decrease in the value of the parameter $X_v(h)$, it shows the physical and mechanical reason for the increase in the hardness number of the material when indented by a sphere. In empirical methods, this property of changing the hardness number with increasing h, F is called the "size effect". Note that there is no Fig.6c in the MCJ ISE method.

For an analytical description of the features of the indentation process with a tool of different shapes and sizes, the development of a method for converting hardness from different scales, standards, a new generalized characteristic of the process (15) Fig.7 was obtained in [2, 3]:

$$X_{SV}(h) = \frac{S_a(h)}{V_a(h)} \qquad (15)$$

$X_{SV}(h)$ is the function of material shaping, the specific area of the surface created (generated) by the indenter in the CI process per unit of the activated material volume. In general, the value $X_{SV}(h)$ depends on the depth h and the shape of the indenter. For a sphere, function (10) has a special property (10.1), $X_{SV}(h)$ does not depend on R, but depends on the indentation depth h and on the value of the parameter δ in the contact surface formula (δ given by a specific empirical technique):

$$X_{SVo}(h) = \frac{S_{ao}(h)}{V_{ao}(h)} = \frac{\delta\pi Rh}{\pi Rh^2} = \frac{\delta}{h}, \quad \delta = 2 \div 4 \qquad (15.1)$$

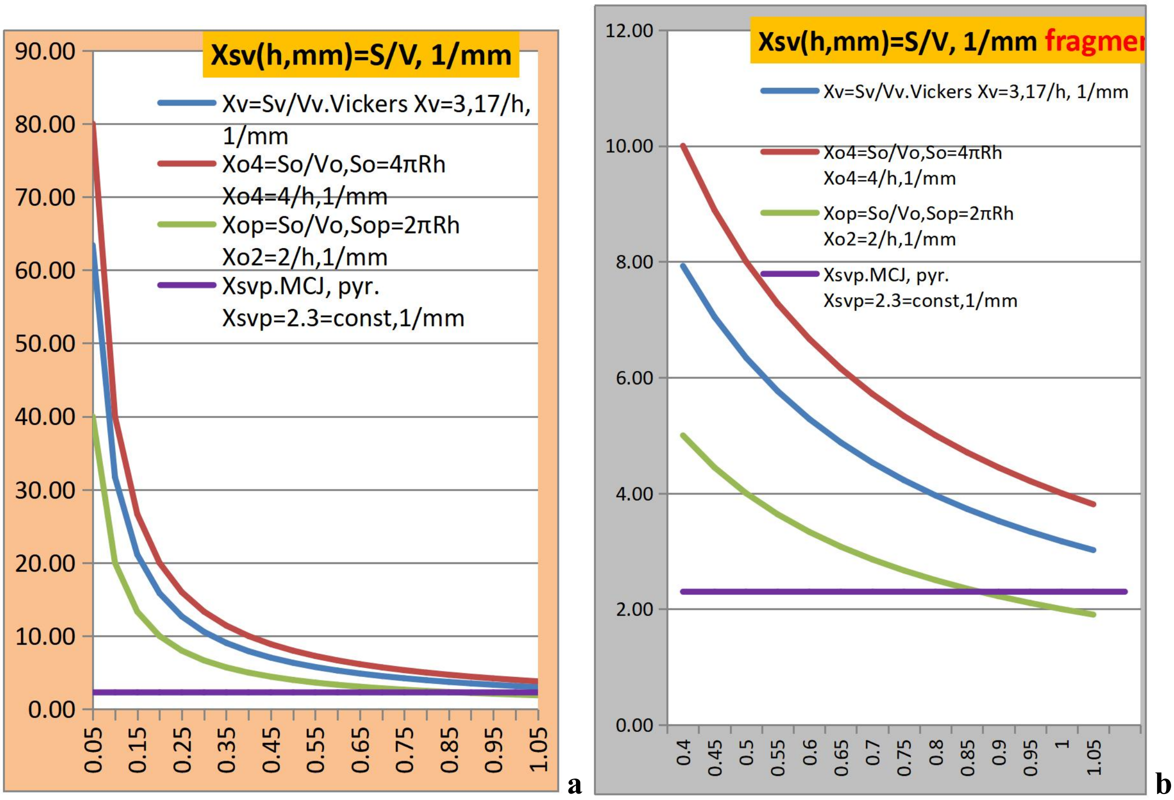
For pyramid: $X_{SVv}(h) = \frac{\lambda}{h}$, (15.2)

Where, λ is the influence parameter of the shape of the pyramid (cone) Sa= λh^2 . For the Vickers pyramid λ = 3.17. Figure 7 shows the functions $X_{SV}(h)$ for the sphere, pyramid and truncated indenter. The specific indicator is indirectly affected by the approximate formula for calculating the contact surface $S_a(h)$, using the example of a sphere, two options are shown, the contact surface So and the projection area of this surface Sop. Necessary physical condition of similarity when measuring macrohardness:

$X_{SV}(h) = const$, (15.3).

From the analysis of the function of physical macrohardness, it follows that for different materials and different shapes of the indenter, the similarity of hardness measurements is ensured if, as a result of moving the indenter by the amount h per unit of activated volume, the same surface area (specific area) of the material is generated, i.e. the same (similar) shape change of the solid body is created: $X_{sv} = const$, where $X_{sv} = S_a(h) / V_a(h), 1/m$

The calculation and comparison of the hardness number of different materials, different indenters, should be performed under similar physical and mechanical conditions - the same increase in the specific area of the contact surface, i.e. area growth per unit of activated (displaced) volume V_a. Studies have shown that such conditions for measuring the hardness of a material were first provided by Calvert-Johnson (1859) [3]. The first physically correct method for measuring hardness was developed in 1859 [4] by Calvert-Johnson, a truncated cone indenter was used, its shape is special, in this case the value of the shape change function does not depend on h, $X_{SVMCJ} \approx const$, see Fig.6,7. MCJ indentation is an ideal process for measuring macrohardness, the shaping function does not depend on the depth h (invariant), $X_{SVPMCJ} = const \approx 2{,}3.1/mm$



Rice. 7. The function of shaping the activated volume $X_{SV}(h)$. Indenter pyramid, sphere, cone MCJ. Sphere: Contact surface $S_{ao}(h) = \delta\pi Rh$,δ=4. Projection Sop, δ=2. Truncated cone MCJ, constant parameter $X_{SVPMCJ} = const \approx 2{,}3.1/mm$

An analysis of the hardness diagram of different materials showed that, with increasing depth h, the contribution of all components of the gradient continuously grows in the sphere $PHMA(V)$ - (11), while the main hardness parameter PHM (10) increases at the same time. If, when determining the physical parameter PHM , the depth standard h_{st} is in the test interval $h^* < h_{st} < h_{max}$, then the discrepancy with the empirical value will be insignificant. With a significant discrepancy between h_{st} and h_{max} , the growth of PHM can be taken into account by a correction constant factor, but at the same time, the ratio should be constant during measurements h_{max} / h_{st} . An example of such a case is below. Let's summarize all of the above. With the help of physical potential (10), (11), an algorithm for determining the value of the standard macrohardness of a material has been obtained; for this, several new simplified physical methods for calculating the hardness number from the F(h) diagram have been developed.

Physical kinetic macrohardness of the material, definition (abbreviated).

Physical macro hardness PH, J/m3 - the amount of mechanical energy dissipated (consumed) during the shape change of the **activated material volume** Va under the action of the indenter pressure. The expended energy or mechanical work of the indenter is calculated per unit of this volume. The activated, displaced material forms a predetermined value of the **contact surface area Sa**. As a result of indentation, we obtain the function PHI(h). When determining the hardness number, we use a standard process, in the indentation, the value of the specific contact surface specified by the standard (Sa/Va value standard) must be formed. **The activated volume** of a deformed solid body **Va** is the volume of material that has been moved, changed its original shape, made internal irreversible structural transformations, generated a new contact surface area as a result of mechanical indentation (kinetic indentation) of an ideally solid body of an indenter of a certain shape into it.

The number of physical macrohardness of the material, PHst, J/m3 is the value of the specific dissipated mechanical energy that must be expended on the process of kinetic indentation, as a result of which a certain volume of material is moved, a certain value of the specific area of the contact surface is formed, specified by the standard or reference method. **PHst** - the value of the function of physical macrohardness, determined for the standard (standard) of the depth h_{st} of indentation performed by the sphere. The diameter of the macro sphere is arbitrary. For macro indenters of a different shape, the macrohardness number, the specific work of the indenter, is found for the reference value of the shape change function X_{SVST} . The standard parameter of the forming function, the specific area of indentation $X_{SVST} = S_a(h_{st}) / V_a(h_{st})$.

Indentation Size Effect (ISE) when measuring macrohardness.

On Fig. 7a, shows in a generalized form the force diagrams $F_n(h, D_n)$ with different process trajectories, different diameters, constant hardness HB=const. Figure 8b shows the corresponding functions $PHI_i(h, HB_i)$ of specific power, three hardness values HB1<HB2<HB3, three sphere diameters, formula (9.6) is used. An analysis of the properties of functions $PHI(h)$, (9.4) and functions of empirical hardness $HI(h)$, (9.5) showed that the hardness number for macro indentation with standard indenters of different shapes should be found only for one established reference value h_{st}. With increasing depth $h_{st} \to h_{sx}$, Fig. 8b, there is a proportional increase in the values of the empirical hardness number, the scale of the

hardness scale changes. A larger value of depth h_{sx} corresponds to a "stretched" hardness scale. Thus, the number of material PHI_i formally increased. The scale with the new hardness scale (dept h_{sx} h) is shown in yellow. The hardness for each HBi measure has increased on all lines of the diagrams PHI_i, and the scale of the empirical diagrams HI(h) will change similarly. As you decrease h_{sx}, the scale shrinks. At the same time, the value of the physical hardness potential $PHM(V)$ of a given material does not depend on h in a sufficiently large CI range; this is a constant physical characteristic of the material, a given shape of the indenter, and a sufficiently large depth interval h. This hardness potential $PHM(V)$ differs from the empirical or physical hardness number obtained by formula (9.4). For the CI diagram built by the MCJ indenter, the physical hardness $PH1_{MCJ}$, component (9.6), is practically independent of depth, it is equal to the physical hardness potential $PHM(V) = PH1_{MCJ} \approx const$.

In modern CI methods, there are no criteria and conditions for maintaining the similarity of ***physical processes when measuring the hardness number***, this is the main reason for the appearance of the size effect (SE). In empirical methods, the measurement of the hardness number is performed at a different, uncontrolled value $X_{SV}(h)$, i.e. under different physical conditions. For the similarity of empirical tests, a sphere, a pyramid, a cone, it is necessary to assign and observe the standard of the physical and mechanical process. For a sphere in macro CI, this is a constant depth h, regardless of the diameter. On the physical conditions of similarity during indentation with other instruments and in different ranges in [2, 3] The truncated cone indenter MCJ provided the same physical conditions in each act of indentation mechanically. In MCJ, under the condition h > h*, an approximately constant specific area of the contact surface is generated $X_{SV}(h) \approx const$, Fig. 6;7. The influence of the relaxation site is small. In MCJ, throughout the entire process of indentation, the amount of specific energy for the formation of the surface of the material, the physical macrohardness, is approximately constant. If the MCJ indenter is used in standard macro CI methods, there will be physical similarity conditions over the entire macro measurement range, ISE is excluded, diagram Fig. 7.

Discussion of the obtained results.

An experimental-analytical physical method for analyzing kinetic indentation data consists in constructing a physical hardness function and determining the number, the value of the physical hardness function of a material at a certain point in the process. These are two objective individual integral characteristics of the kinetic indentation process. The kinetic method of indentation analysis is based on the principles of the physical structural-energy theory of the strength and durability of materials [7]. The task of my research is to present the physical theory of hardness of kinetic indentation as a special case of the physical theory of strength DB. On these theoretical principles, using indentation, to develop methods for determining the universal physical parameters of hardness, durability, strength, plasticity of materials. At this stage, we have considered three different characteristics of the process of determining the physical hardness of kinetic macro indentation with a sphere:

1. $PHMA(V)$ J/m^3 - function of the potential of the specific generalized power of macroindentation of the material, volumetric derivative (7), gradient (11).

2. $PHM = \frac{\Delta A}{\Delta V} \approx \frac{dA}{dV} = const$, J/m^3 , is the parameter of the physical potential (9), the volume derivative of the linear function $PHMA(V)$, a constant value for the laminar process of material indentation. A simplified version of calculating the value of the physical macrohardness of the material, using for this a linear trend of the function of the physical thermomechanical potential $A(V, m^3)$.

3. $PHI_x(h, HB) = \frac{a_o h^2 + b_o h}{\delta \pi R h}$, J/m^3 (N/m^2) - the main component of the gradient of physical hardness of laminar macroindentation (12.3) , constants (8) of the approximation of the function $F(h)$. This is a simplified formula for the empirical macrohardness function, at the same time it is a component of the material's physical macrohardness. The formula was obtained for the laminar process of indentation by a sphere.

Analytically, any of these three characteristics can be obtained, having a record of the experimental force diagram F(h) or the values of the parameters a_o, b_o (8) of the approximation of this function and the value of the diameter D of the sphere.

$PHMA(V)$ J/m^3 - physical function of the macrohardness potential, a new integral generalized characteristic of the property of the indentation process obtained in the interval $h_* - h_{max}$.

PHM , J/m^3 - parameter of physical macrohardness, stable characteristic of a homogeneous isotropic material, integral physical characteristic of the process of _laminar indentation by a sphere._ The parameter is determined in a wide range of indentation depths $h_* - h_{max}$.

PHM analytically related to the number of empirical standard hardness on the Brinell scale. Table 3 shows an example of parameter calculations for four different steels.

Universal physical unit of macro hardness.

Taking into account the important role of the Calvert-Johnson method in the formation of modern indentation methods, the appropriateness of the application of physical theory and the new unit of hardness, I propose to approve the universal physical unit of macrohardness as a standard:

$1.CJ = 1 \cdot 10^7 J/m3$, 1.CJ - one "caj".

The hardness of a 103HB standard measure is approximately equal to 100CJ physical hardness. Physical macrohardness of structural materials is in the range of 1-1000CJ, does not depend on the shape of the indenter. The function, scale and values of physical hardness are analytically related to the function and number of empirical hardness, for different indentation methods. Physical and empirical methods can operate for the necessary time in the new standard at the *same time, until the cancellation of empirical methods.*

Example. Estimation of physical parameters of hardness of steels.

An example of using the method of physical analysis of indentation. On Fig. 8 indentation force diagrams obtained at the IPP NASU [16], four high-quality steels were tested, the standard Brinell hardness, the sphere D2.5mm, was determined. The method of increased accuracy was used, diagram F(hp), where hp is the plastic displacement component, h>hp, h is the standard value of the indenter displacement. In analytical methods for analyzing the physical parameters of the indentation process, the linear diagram F(hp) has an advantage. The diagrams show the equations ($F = kf \cdot x, N$), where $kf, N/m$ is the linear trend parameter, obtained by me as a result of approximating the test graphs [16]. To study the properties of a new physical method for determining hardness, these experimental results can be approximately taken as similar physical conditions, deviations from the conventional depth standard are small.

Using numerical methods of analysis, we find the integral of the function F(hp), (6.2) - A(hp), the work of the indentation process and, at the same time, the function of the thermomechanical potential of a given TMS (Thermomechanical System). Using Excel approximation methods, we construct A(V) diagrams for these steels. Let's determine the linear trend of each diagram, find the linear trend parameter (9) - PHM, J/m3, physical potential macrohardness of steel. In Table 3, the results of determining Brinell macrohardness and physical hardness by different methods: BH - State Standard 9012-59, ISP NASU kinetic indentation method [16], PHM $J/m3$ - physical potential macrohardness, is calculated by formula (10). PHMC, $J/m3$ - correct physical potential macrohardness, k_{CR} - Correct choreic-rheological nondimensional coefficient: $k_{CR} = PHM/BH$.

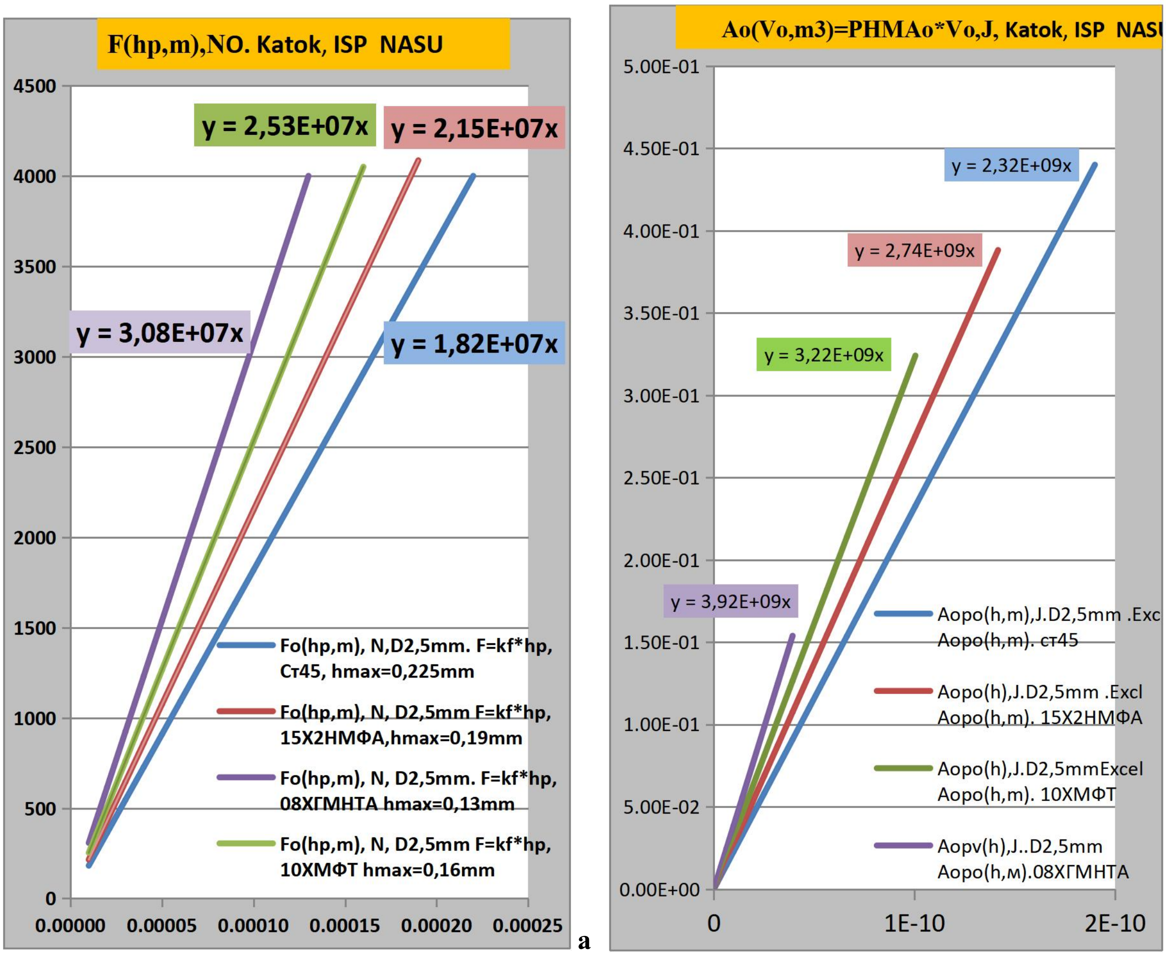


Fig.8. ***a.*** Experimental diagrams F(hp), hp is the plastic component of displacement, steels 45, 15Kh2NMFA, 08KhGMNTA, 10KhMFT were obtained using a special IPS method [16], for measuring Brinell hardness, D2.5mm; **b.** Function of the thermomechanical potential of the activated volume of steel, indentation with a sphere D2.5mm, integral of the function F(hp), according to (6.4), Excel approximation method.

Table3. Brinell hardness, BH State Standard 9012-59, kinetic indentation method ISP NASU [16], PHM physical potential macrohardness, PHMC correct potential.

Steel grade	**State Standar**	**Prove n metho**	**Physical potential macrohardness PHM**	**choreic - rheologic al**	**Correct Physical potential macrohardness**	$k_f = \Delta F / \Delta h$ $N / m \times 10^5$

	d 9012-59 BH, $\times 10^7$, Pa	d ISP NASU $\times 10^7$, Pa	$\times 10^7$, Pa	coefficient k_{CHR}	PHMC= $k_{CHR} \times PHM$ $\times 10^7$, Pa	
1	2	3	4	5	6	7
08ХГМНТА	306	301	392	0,8	314	308
10XMFT	255	254	322	0,8	258	253
15X2HMFA	222	223	274	0,8	219	215
45	183,7	189	232	0,8	185,6	182

These results confirmed the validity of the theoretical physical method, and the basic formulas (9, 10, 11; 12.3). A physical simplified method for determining the macrohardness number of kinetic indentation of a material has been obtained. Analysis of the results showed that, in the general case, the empirical hardness represents only a part of the physical hardness gradient, a part of the total specific physical power of the indentation process.

Applying the function F(hp), we presumably obtained the function of the ideal laminar process of macroindentation, while formulas $A_x \approx A$ (12.1) , (12.6) , are applicable $PHI_x(h, HB) = PHM$, $k_{CHR} = 1$, this is the case, the calculation confirmed this property.

Prospects for the application and development of physical methods in indentation.

Physical analysis of the BD indentation charts revealed new analytical hardness properties that are being used in my new applied CI analysis techniques. Briefly the essence of some characteristics.Table 3, item 7 shows the values of the partial derivative of the force function: F´h = ∂ F/ ∂ h for different steels. In this case, the linear function F(h): $k_f = F'_h = \frac{\partial F}{\partial h} \approx \Delta F / \Delta h$, in Fig. 8a calculation results, k_f is a parameter of the linear trend equation $F = kf \cdot x, N$. A stable correlation was obtained experimentally for the values of the generalized growth rate of the indentation force (column 7) and Brinell hardness $F'_h = k_f$

(columns 2 and 3). An analysis of the properties of the obtained formulas showed the physical basis for the correlation of values, a simple formula for the normalization factor was theoretically obtained kn, for calculations in the first approximation of the standard hardness by the value $BH = kn \cdot k_f, Pa$ of the generalized indentation speed. A supposedly new method for calculating the empirical Brinell hardness number has been obtained. At the same time, the validity of the laminar process model by a macro CI sphere was experimentally confirmed:

$$k_f = \frac{\partial A_x}{\partial V_x} = \frac{\partial F}{\partial h} \approx \Delta F / \Delta h$$

These results have shown the important role of the concept of generalized velocity in the analysis of the parameters of physical CI processes. In particular, in further studies of physical hardness, the generalized growth rate of the specific thermomechanical potential of indentation (physical hardness) and the generalized growth rate of the indentation force ($F'_h = k_f$) and others have been successfully used.

In works [2,3], the generalized rate (power) of changing the process parameters was used to determine the parameters of the physical equations of sharp tools (cone, pyramid.), the physical parameters of the nano-micro range hardness, and to determine the universal physical molar strength parameters.

On Fig. 9 shows a new generalized physical characteristic of the kinetic indentation process (built by the Excel method), Aopo(Xsv) is a function of the thermomechanical indentation potential , where Xsv is the argument of the function in the kinetic process of potential. As a result, similar hyperbolas are obtained, each characterized by one own parameter Daxo . On the graphs, this is the coefficient of the hyperbola approximation function: $y = D_{axo} x^{-2}$. On the physical meaning of this new characteristic. In standard kinetic indentation, an approximately constant tool speed is used $\upsilon_i = const, m/s$. Therefore, we have $h = \upsilon_i t, m$. In this case, the depth can be considered as a generalized time coordinate of the indentation process: $h \sim t$ .From (15.1) , $X_{SVo}(h) = \frac{S_{ao}(h)}{V_{ao}(h)} = \frac{\delta}{h}$ Where δ is the shaping parameter. For a sphere in the macro range $\delta = 2 \div 4$. In the general case, a non-linear function, depends on the shape of the tool. As a result, we will get a new formula and a function of the connection between the energy potential A and the speed υ_x :

$$A(X_{SVo}(h)) = A(\upsilon_x)$$

Where $\upsilon_x = \frac{\delta}{h}$ is the generalized rate of change of the contact surface shape parameter. Thus, in Fig.9, at the same time, the diagram of the thermomechanical potential $A(\upsilon_x)$,J depending on the generalized speed of the contact surface shape change .

Based on the studies [3], the physical and mechanical processes of indentation are divided into three ranges Fig.9: TMSM, COMBI, TMSN.

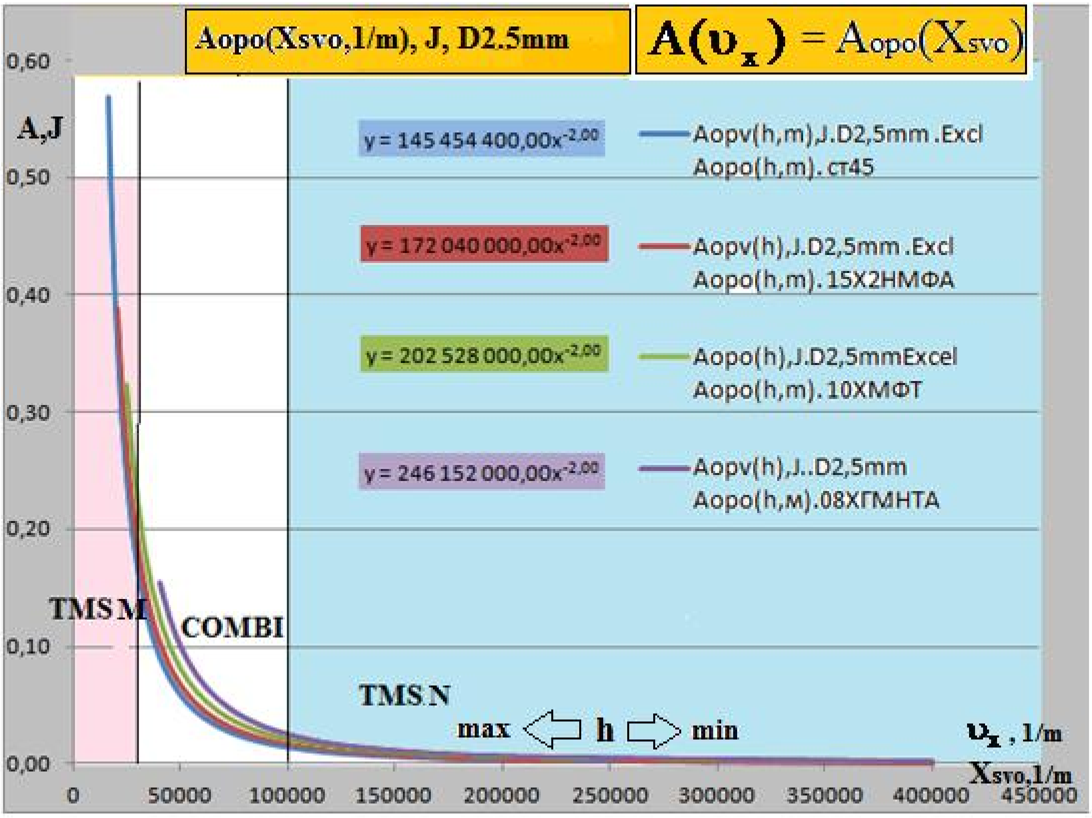


Fig.9. Dependence of the thermomechanical potential of kinetic indentation A,J on the value of the generalized indentation speed υ_x as well as on the shape change: $A(\upsilon_x)$ = Aopo(Xsv), J.Division of physical and mechanical processes of indentation into three ranges: TMSM, COMBI, TMSN.

Macro range of kinetic indentation - TMSM. Nano-micro indentation - TMSN. This range, according to its physical and mechanical parameters, is classified in tribotechnics as a tribosystem [17]. When indenting with a sharp macro indenter, joint processes are observed [3], the range is COMBI. In each range, own physical equations and hardness parameters are obtained, they are analytically interconnected (a correlation is established) with the universal molar physical parameters of the durability of materials [4].

Based on the developed physical theory of indentation, the next stage was completed - the basis of the theoretical method for determining the universal physical parameters of strength and durability was created. At the moment, the main elements of analytical methods for determining the limiting standard indicators of strength and fatigue of structural materials have been tested. In particular, using the physical molar parameters, it is analytically possible to determine the standard limiting mechanical strength characteristics. In [18], the method of analytical virtual computer testing of steel 45 is shown, the calculation is performed on the basis of physical equations and parameters, the standard characteristics of ultimate strength, fatigue limit at different temperatures and cycle rates, etc.

My research work is aimed at creating the physical mechanics of a deformable solid. At this stage, I have developed several methods for calculating the universal physical molar parameters of structural materials based on the physical parameters of hardness. Figure 10 shows in a generalized way the properties of physical hardness diagrams for the three ranges of utilitarian use of CI. These results need to be optimized and verified in detail for the subsequent development of engineering and scientific CI programs.

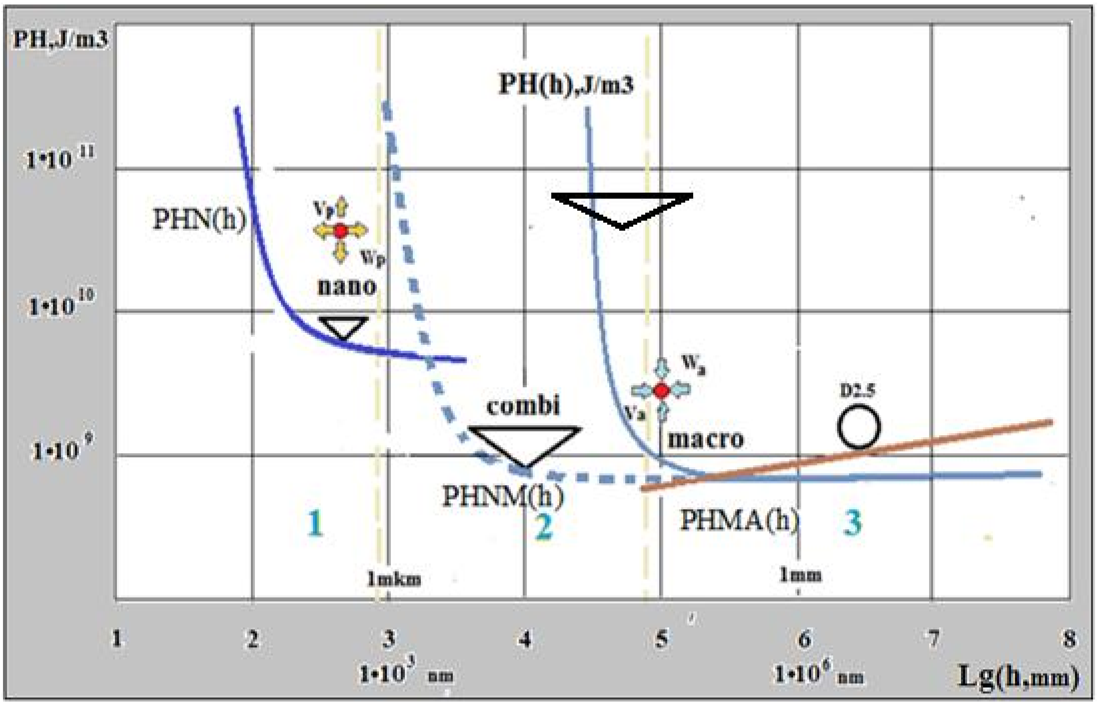


Fig. 10. Characteristic diagrams of physical hardness PH(h) of indentation, pyramid of different sizes, macrosphere, depth scale Lg (h, mm). Vertical yellow dashed lines are conventionally the boundaries of three ranges: 1-nano; 2 - nano-micro, micro-macro (combi); 3 - macro. The diagram in brown is the macro mode for the sphere D2.5mm [3].

Figure 10 plots in three different indentation ranges (gradation according to ISO 14577) diagrams of physical hardness PH(h) J/m3, [3], from the comparison, it is obvious that the initial power of the process of forming and structural transformations of the material in the nano mode is -1 PHN is 100-1000 times greater than the macro mode -3 PHMA. This result is consistent with the conclusions of the experimental work [19], which shows that the specific energy of nano-destruction exceeds the macro-indicator of the energy density of destruction by 100-1000 times for conventional tests for ultimate strength. These results confirm the assumption that the nano-micro range of indentation has a special physical mechanism of its own, its specific power is many times greater than that of the macro range [3].

The new methodology for analyzing the results of kinetic indentation makes it possible to systematize the measurement processes with different tools and methods and provides a theoretical basis for the development of universal physical methods for measuring micro and nano ranges of hardness.

In the perspective of this work, a new simplified technology for performing kinetic indentation is being prepared, based on new principles for processing force diagrams of indentation. The new technology lacks special processing and surface preparation, reduces the requirements for measurement accuracy, etc. New analytical methods for analyzing the F(h) diagram have been developed. The physical method in indentation has advantages, it allows the use of a portable (mobile) tool and new technologies, simple analytical methods for processing data from the kinetic indentation process.

I offer joint research to interested organizations and specialists. I offer joint research to interested organizations and specialists.

Findings

1. Methods for the physical analysis of force diagrams of kinetic macroindentation obtained according to ISO 14577 have been developed.

2. Based on the physical analysis of the experimental data of the process of kinetic macroindentation, a physical model was built, the thermomechanical potential of the state of the material activated by the indenter, the similarity criterion was determined, the function and hardness number of kinetic macroindentation by the Brinell sphere were determined.

3. A method for determining the universal standard of macrohardness of a material is shown, the relationship between the standard empirical and physical macrohardness of materials during kinetic indentation with a sphere is analytically established. The physical universal standard of macrohardness of kinetic indentation of a material does not depend on the geometry of the tool.

4. The physical cause of the size effect in standard empirical methods of macroindentation is revealed.

5. A theoretical foundation has been prepared for the development of physical methods for kinetic indentation with a pyramid, cone, nano-micro indenter.

6. Physical universal stable, integral characteristics of kinetic macroindentation, methods for measuring the function and number of physical macrohardness, criteria for similarity and comparison of values of empirical (standard) and physical hardness of materials are proposed.

7. A theoretical basis for the improvement of the ISO 14577 standard has been created.

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