

Part 2.1 - 2.3

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1.

Introduction. About the hardness of materials.

Modern indentation is a widespread multifaceted operational method for assessing the hardness, nano-micro structural and physical-mechanical properties of materials and thin coatings. Existing indentation methods can be divided into three historically formed directions:

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

At present, there are a number of scales, standards and methods that do not have a well-founded 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 of the value has been established. 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, from [1] in abbreviation. Indentation of a material is a common experimental and analytical approach to determining the hardness number of a material, performed by different tools, etc. Hereinafter, we briefly call this modern approach empirical single-act hardness - EH (Empirical Hardness). Under this designation we mean methods of single-act macro surface empirical indentation. Instrumental kinetic indentation is considered separately. Generally accepted characteristics in EH indentation methods: force F , indenter movement h , conditional indentation area S (the calculation formula depends on the method), etc. EH does not have a physically and theoretically substantiated definition of hardness [1,2,3]. Hardness values obtained by EH methods do not have a clear physical content and are not correctly comparable. Briefly, it can be formulated: empirical standard hardness solves problems as a more convenient, accurate, and faster way to measure and compare the hardness number of different materials or quantitatively evaluate their different structural and mechanical states.

Based on the analysis of theoretical and experimental data, in the works [1,2,3,15] it is shown that the development of standards and improvement of methods for measuring empirical hardness (EH) without a physical theoretical justification for the concept of material hardness has no prospects. For an operational and informative solution to the problems of assessing the strength, damage, brittleness and stress state of the material in the elements of critical machines, high-rise structures, unique structures, etc., the development of new effective universal physical methods for analyzing test data on the physical and mechanical properties of materials obtained by means of KI is relevant. To develop and improve new methods for analyzing data from kinetic indentation of materials, I began theoretical preparation of the basic principles and methods of the physical theory of hardness. Below are the theses and brief main provisions of the physical theory of hardness of kinetic indentation, partly reflected in the works [1,2,3,4]. Here are examples of physical analysis of different types of force diagrams $F(h)$, comparison and discussion of empirical and physical methods, application of the obtained results for operational assessment of the property of hardness.

Physical hardness poses the problem of how to obtain experimentally and analytically a physical characteristic of the process of interaction of a very hard body of an indenter and the studied material, to construct analytically the function of the process, to determine the standard physical quantity, unit and measure of this process, to show the physical relationship of hardness, strength and other physical and mechanical properties of the material. The above also applies to scratching methods. Studies have shown that canonically the EH number of hardness, regardless of the technique, is, in essence, the ratio of some specified test force F on the indenter and some conventional area S . We indirectly associate this area with the size of the contact surface of the tool and the material. The formula for calculating S is empirical and depends on the method. There are no physically correct principles for choosing the force F and area S in EH methods. Therefore, the EH value can be considered as a correlation number or function, conventional specific force, incorrect value of pressure or compressive stress: $EH = F / S$, N / m^2 . The dimension of hardness is often not indicated, and a dimensionless designation is used. Let us add that in physical methods of analysis of thermodynamic mechanical systems, the magnitude of stress and pressure represent ambiguous characteristics of processes. To

calculate limit states, etc., they require additional functions, equations and parameters. The ambiguity of the EH hardness indicator is a consequence of the simplified representation of the complex thermomechanical system "indenter - material - mechanism". We will further designate this system as TMS (Thermomechanical System) [3].

In general, it can be said that with the help of empirical methods of hardness testing, various tools and technologies are used to determine some correlation parameters, which are historically called the hardness number of a material. My analysis of the development of methods for determining the number and KI hardness diagrams showed that at the beginning of the formation of the concept of hardness, a physical method was created and the first dimensional physical correct scale, the Calvert Johnson (MCJ) method, was formed [16]. Subsequently, it was utilitarianly transformed into a dimensionless scale. The physical basis and theory of the MCJ hardness measurement method have remained undisclosed to this day.

Comparative methods of EN are acceptable for solving specific applied problems in materials science, metallurgy, mechanics, etc. The construction of a general physical theory of kinetic indentation, systematization and justification of a physical unit of hardness, the creation of a universal measurement standard and a single correct method for comparing the hardness number in different standards and ranges is an urgent task today. Applying the theory, we will reveal the physical meaning of the fundamental method for determining the hardness number MCJ (1859) and then use its theoretical basis to analyze and improve the KI methods and measure the hardness number. Then, we will apply the developed physical method for analyzing the MKI diagrams to analyze the diagrams of uniaxial tension of material samples before their destruction. As a result, we will obtain a physical general universal method and a quantitative measure (algorithm) for analyzing the state of a deformable solid for experimental and analytical evaluation of the parameters and properties of hardness, strength, durability, brittleness of materials directly in structural elements. As a result of the work done, the physical theory of hardness was combined with the physical structural-energy theory of the strength of materials.

Let us consider the properties of the physical hardness function, in particular its main component $PH_{ix}(h)$, and establish the relationship between physical and empirical hardness using the Brinell scale as an example. Let us briefly cover the main results of the physical theory of hardness (PTH), which were obtained in [3,4]. Universal physical unit of hardness, comparison criteria and method for converting empirical hardness number values from different scales into a single physical scale, into a universal unit of hardness, etc. Principles of new methods of physical analysis of macro KI force diagrams (hereinafter MKI) obtained for a sphere and a pyramid. In the first half of the work, we will consider an example of using the methods of the theory to determine the function and number of physical hardness based on the MKI process data for steels. Let us calculate the hardness values of steels using new simplified analytical methods. Here, the results and conclusions are presented mainly in relation to macro indentation. The experimental KI data for my research were provided by Professor V.I. Moshchenok [15], also from open scientific publications and kindly provided by the management and specialists of the ISP of the National Academy of Sciences, Kyiv, Ukraine [17].

PTHS divides KI processes into three ranges (gradation according to ISO 14577-1). For this purpose, three methods of analysis are theoretically used [3]: 1 - nano-micro NMKI, 2 - combined COMBIKI, 3 - macro KI (for $D > 2.5$ mm, the designation MKI is used below). Here we will consider the 3rd physical method of MKI analysis. Fig. 1 shows KI force diagrams with

a sphere $F(h)$ and a process diagram in the activated volume of the material. Designations: V_p m³ is the physical activated volume PSB of the thermomechanical system (TMS) "indenter - material - mechanism", V_a is the geometric volume of the body displaced (moved) by the indenter, calculated using the empirical formula of the selected method. v_i is the indenter, $v_i = dh/dt$, m/s is the displacement speed, S_p is the area of the physical surface of the activated physical volume of the material V_p , T is the temperature V_p . In the laminar MKI process, it is assumed that the activated physical volume V_p and the geometric volume V_a are equal: $V_p = V_a$. For the MKI case, we assume that $S_p = S_a$, where S_p is the area of the contact surface and S_o is the area of its projection, F , N is the force, $x = h$ is the indenter displacement. The diameter of the sphere is D (radius is R). A is the thermomechanical potential V_p . For the MKI process with a sphere or pyramid, we assume that the equality is true:

$$V_p = V_a = V(*).$$

Where, V is the volume of material displaced by the indenter along the X axis, the lower index is sometimes omitted for simplicity. In the general case of KI, in different ranges, we have a difference in physical and geometric volume: $V \neq V_p$.

Using the physical analysis of the characteristic force diagram MKI (Fig. 1a), dependencies (1.1), (1.3) we obtain the function of specific generalized power. We use the approximation of the function $F(h)$ by the polynomial (1.4) [15],

$$F(h) = a_{o,v} h^2 + b_{o,v} h + c, \quad (1.4)$$

$$F'_h(h) = \frac{dF}{dh} = 2a_{o,v} h + b_{o,v}. \quad (1.5)$$

$$k_{\dot{h}}(h, HB) = F'_h(h, HB), N/m \quad (1.6)$$

Where, $a_{o,v}$, $b_{o,v}$, are constants, parameters of the method, depend on the indenter shape and material hardness, for KI by a macrosphere, the subscript "o" is a sphere indenter, "v" is a pyramid or cone indenter. $k_{\dot{h}}(h, HB) = F'_h(h)$ is the generalized rate of change of the indentation force $F(h)$ [s]. According to ISO 14577-1, v_i , the indenter movement speed is recommended to be approximately constant, $v_i = \text{const}$, m/s = $h' = x' = \partial h / \partial t$. Based on these standard requirements, the movement is proportional to the test time: $h \sim t$, where t , sec is the time, therefore v_i , N/m can be represented as the generalized velocity of KI. Let us study the physical properties of function (1.1) using MKI as an example. According to the general field theory, the volume derivative (2) is a function of the potential of a scalar field with the macro potential of energy $A(V)$, and it is also the specific generalized indentation power, which is equal to the energy density gradient [3].

According to the PTH process model Fig.1b, the stress and temperature fields at the boundaries of the surface S_a , S_p of the volume $V_p(h)$ are formed by the power flows CVW of energy in the volume V_p [4]. Using the concept of the gradient of the scalar field of potential energy A in the volume V_p , we find three components of the gradient of the potential field (2) on the surface S_p [4]. Here we restrict ourselves to the variant of a scalar homogeneous field, but in

the general case the potential grad A is a vector field and it is necessary to consider its divergence. The components grad $A_{x,y,z}$ are vectors (2.1), they are directed along the coordinate axes, these are the flows of the generalized power CVWE. In the volume of a solid, these flows associatedly form the components of the power CVWE of the pressure forces (stress) [18] and simultaneously the flows of thermal power (form a temperature field). In the KI process, these components form the total specific power of the power flow (flows of specific energy) of the activated volume – the physical hardness PH. We will further study the rheological component of the volume derivative function of potential A, as its integral part, separately.

2.1 Properties of the function gradA - specific volume generalized power MKI, definition of the concept, function and number of physical hardness. The main component of physical hardness $PH_x(h)$, $HI(h)$, standard function $PHst(h)$ and standard number of hardness $PHst(hst)$.

Let us consider the physical properties (2), (2.1). Let us analyze the properties of function (2) for the potential A as a scalar field CVWE in the volume V_p , in Cartesian coordinates [3]. We assume that the MKI process occurs in an isotropic body, from (1.1), (1.2), we obtain (2)

$$PH(V) = \frac{dA(V)}{dV} = \text{grad}A = \frac{\partial A_x}{\partial V_x} + \frac{\partial A_y}{\partial V_y} + \frac{\partial A_z}{\partial V_z} = PH_x(V_x) + 2PH_{y,z}(V_{y,z}), \quad (2)$$

$$\text{Где, } PH_x(V_x) = \frac{\partial A_x}{\partial V_x}, PH_y(V_y) = \frac{\partial A_y}{\partial V_y}, PH_z(V_z) = \frac{\partial A_z}{\partial V_z}, PH_z = PH_y \quad (2.1)$$

Где, $\text{grad}A$, J/m^3 - вектор градиент макро потенциала поля $A(V_p) = A(V)$, далее нижний индекс p и x опустим: Where, $\text{grad}A$, J/m^3 is the vector gradient of the macro potential $A(V_p) = A(V)$ of the field, and we will omit the subscript p and x below: $V(h) = V_x(h) = V(h)$.

Equation (2) displays the MKI process presented by a simplified model based on continuum mechanics, the solid here is a continuum, homogeneous and isotropic. Here, the fine structure of the torsion field of vortex wave corpuscular processes of motion and transformation of internal energy power flows is ignored. The physical deformed solid is represented by a torsion field, a space filled with CWVE. In phenomenological theories, the solid is modeled by structures of atoms, dislocations, lattices, blocks, etc. The features of the influence of the structural-energy state of the solid on the PHKI, PHUTM functions, the influence of the absolute size of the activated volume (nano, micro, macro) and other parameters on the value of the energy density and specific power and the potential of physical hardness will be considered below.

From the comparative analysis of the property of the total power potential, (2) and the function of the principal component of hardness (3) it can be assumed that their values, under similar conditions of hardness testing, differ by some constant factor k_{CHR} see (2.2). In particular, if during MKI testing the values of the physical potential of a material of different hardness we take a constant value of the depth hst (respectively, a constant V_{ast}), then the correction factor is constant [1,3]:

$$PH_x(h, HB) = k_{CHR} \cdot PH, \quad k_{CHR} = \text{const}, \quad (2.2)$$

Where k_{CHR} - choreic – rheological coefficient.

This property was tested on experimental data for MKI of standard measures of different hardness.

In cases of MKI the process can be represented as laminar, we will consider it separately, while $k_{CHR} = 1$, as a result we obtain:

$$PHI_x(h, HB) = PHM, \quad (2.3)$$

For the laminar process of MKI with a sphere, at $D > 2.5$ mm, cyclic indentation [3]:

$$k_{CHR} \approx 0,8 = \text{const}.$$

In the general case, for an arbitrary indenter shape, for different MKI speeds, different depths - h , nano-micro volumes - V , and long duration of the KI process - t , we have a complex function $k_{CHR}(t, V, h, \nu_i)$.

To assess the degree of influence of the remaining two components of the tensor (2.1) on the function of the principal component of physical hardness, we consider the gradient (2) using the factors S, V, h, t , and represent the potential of physical hardness A_x as the sum of its three components. To do this, we use the formula for the potential A for three components forming the full potential of specific power (1.2):

$$A = AS + AV + At, \quad J$$

Let us select one component along the X axis from the full three-dimensional potential tensor A , and obtain:

$$A_x = A_xS + A_xV + A_xt.$$

Using this formula, as applied to the principal component of specific power $PHI_x(h)$, we obtain (2.4):

The thermomechanical potential of the component A_x (the main part) is directly dependent on the sum of the three potentials of the components of the specific indentation power. Potentials $PH_{s,v,t}$ are divided into three characteristic physical processes:

$$PHI_x(V) = PH_{s,v,t} = PH_s + PH_v - PH_t, \quad (2.4)$$

Each component of the specific power, physical hardness is designated by its subscript s, v, t : $PH_{s,v,t}$. The component is only part of the total potential of physical hardness. Each of them shows the contribution to the total power of different processes of the power of the internal energy dissipation flows occurring at three levels of nano, micro and macro KI. From (2.2) we obtain:

$$A_x = A_{xS} + A_{xV} + A_{xt} = V_s \cdot PH_s + V_v \cdot PH_v + V_t \cdot PH_t. \quad (2.5)$$

$$\Gamma_{де}, \quad A_{xS} = V_s \cdot PH_s, \quad A_{xV} = V_v \cdot PH_v, \quad A_{xt} = V_t \cdot PH_t \quad (2.6)$$

Where, $PH_s, (S/V \rightarrow \infty)$ is the surface specific power of irreversible processes; $PH_v, (S/V \rightarrow 0)$ is the volumetric power; $PH_t, (S/V = \text{const})$ is the rheological power.

Each component of the potential PHs, PHv, PHt has its own size of the activated physical volume $V_{i=s,v,t}$. The definition of components (2.6) is given in more detail in a separate article. Further, for simplicity of notation, the lower index "p" of the physical volume is omitted. V is the activated volume of material displaced, moved by the indenter along the X axis, $h=x$:

Formulation of the definition of physical hardness. Standard function PHst(h), standard hardness number PHst(hst).

Physical hardness KI: PHKI(h) J/m³ is the volume derivative of the function of thermomechanical potential A, the function of the specific (volume) generalized power of the kinetic (instrumental) indentation process, the physical function of the state of the KI process, relative to the variable h. The second option, the volume derivative relative to the independent value of the activated (displaced) volume Va. A,J is the thermomechanical potential, the value of the transformed, dissipated energy in the activated volume Va of the deformed body, the mechanical energy expended on moving an absolutely rigid indenter body into the material by the value of h or Va.

Standard function of physical hardness PHI(h) is the analytical form of recording the function obtained on the basis of the standard experimental process of macroindentation. The reference parameters are set: speed KI, temperature, size and shape of the indenter, etc. material with reference hardness.

PHst is a number, a standard of physical hardness, the value of the KI function at a specified point of the standard indentation process hst, a characteristic of the structural and physical state of a given material. $PHst = 1$ physical unit of hardness. In [1,2,3,4] a universal physical unit of macro-hardness 1CJ is proposed. The value of the function of the specific generalized power of material indentation at a point of the process specified by the standard. PHst is the amount of energy that must be dissipated (expended, transformed) in a unit of activated volume of material. The indenter is moved to a depth hst specified by the standard. The material hardness number is tested at the moment of formation of a specified value by the standard of a new free contact surface Sast. Hardness testing is performed during a standard period of time tst, at a constant standard generalized and rheological indentation rate.

2.2 Physical method of analysis of F(h) MKI diagram. Method 1. Calculation of the component of the physical hardness function. Relationship of the function and the number of physical hardness with the empirical hardness on the Brinell scale. Standard hardness number. Function of the generalized rate of growth of the indentation force.

To study the properties of empirical macro-hardness, from the gradient of the physical hardness function (2.1), we select the main component $PHI_x(V_x) = PHI_x(h)$. For the function, two methods for determining the physical hardness of a material using the force diagram F(h) MKI were analytically obtained. Method 1 uses the variable h, Method 2 considers the independent variable V. Using these methods, we study the properties of the physical hardness of a homogeneous isotropic stable material under conditions of mechanical deformation of a solid by indentation and uniaxial tension.

Methods of physical analysis of the F(h) MKI diagram, calculation of the hardness function.

Method 1. Using the F(h) diagram, we analytically determine the function of the principal component of physical hardness and the value of the standard hardness number PHst . We will analyze the function of the principal component of physical hardness $\mathbf{PHI}_x(\mathbf{h})$ obtained from (2.1) on the basis of the F(h) diagram. We will establish an analytical relationship between the physical and empirical hardness functions HI(h). We will determine the physical standard of the hardness value for the function . Using this method, we will consider the physical principle of determining the empirical Brinell hardness number HBW.

Research and calculations were carried out based on the data of one-act MKI tests of standard hardness tests, experiments by V. Moshchenok [1]. Then, calculations were performed on cyclic and conventional kinetic F(h) diagrams for steels, experiments were performed by ISP NASU [14]. Method 2 is considered in the next part of the abstract, it has a difference Va is an independent variable, in this case we obtain the full differential of the function PH(Va) (2) for physical hardness.

Let us consider the gradient component $\mathbf{PHI}_x(\mathbf{h})$, (2.1) axis $x = h$, then we apply to it the term the main component of the full macro potential of physical hardness, this is also the flow of work, energy CVWE in the direction of the vector F(h) [4]. Let us consider the properties and connection $\mathbf{PHI}_x(\mathbf{h})$ with the function HI(h) and the standard number of empirical hardness. Two variants of analysis are shown below, the first uses direct calculation of the derivative (2.1), the second method uses parametric functions, it defines partial derivatives with respect to time of the main functions $A'(t)$, $V'(t)$ for the MKI process.

For average values of depth h, MKI sphere, on the interval $h_1 < h < h_2$, from (1.3), (2), (2.1), if it is true:

$A_x \approx A$, [3,4] , $h_1 = 5 \cdot 10^{-5} \text{ m}$, $h_2 = 1,5 \cdot 10^{-3} \text{ , m}$, in the first approximation:

$$\mathbf{PHI}_x(V_x) = \mathbf{PHI}_x(h) = \frac{\partial A_x}{\partial V_x} = \frac{A'(h)\partial h}{V'(h)\partial h} = \frac{A'(h)}{V'(h)} = \frac{F(h,R)}{V'_x(h)} = \frac{F(h,R)}{\delta\pi Rh} \approx \frac{F(h,R)}{S_{op}} , \text{ J / m}^3 , (3)$$

Where, from (1.3) follows $A'(h) = F(h, R)$, $V_x = V(h)$, $V'_x(h) = S_{op} = 2\pi Rh$ - the projection area of contact of the sphere, here the empirical coefficient $\delta = \text{const } \delta = 2$, from the assumption of equality $V_p = V_a$ (*). In the general case $V'_x(h) = \delta\pi Rh$, where $\delta = \text{const}$, depends on the shape of the indenter, on the type of formula for calculating the empirical hardness S [4], the range of values of the parameter $\delta = 2-4$. In the calculations, its specific value is indicated. For Sop the value $\delta = 2$.

From (1.1), (1.4), (3) we obtain the function of physical hardness $\mathbf{PHI}_x(h, a_o, b_o, R)$.

$$\mathbf{PHI}_x(\text{HB}, h, a_o, b_o, R) = \frac{\partial A_x}{\partial V_x} = \frac{F(h, R)}{V'_x(h)} = \frac{F(h, R)}{2\pi Rh} = \frac{F(h, R)}{S_{op}} = \frac{a_o h^2 + b_o h}{2\pi Rh} = \frac{a_o h + b_o}{2\pi R} . (3.1)$$

Where, for a sphere , $V'_x = \partial V_x / \partial h = (\pi Rh^2)' = 2\pi Rh \cong S_{op}(h)$, $V_{xo}(h) = \pi Rh^2$.

Fig. 2 shows the characteristic diagrams of empirical and physical hardness $\mathbf{PHI}_x(h)$ for a sphere and pyramid indenter. Finally, for the case of nonlinear F(h), using the parameters of the polynomial (1.4), we obtain in general the function of the principal component of physical hardness for a sphere, this is a linear function of h, example Fig. 1, MKI sphere:

$$\text{PHI}_x(\text{HB}, h) = \frac{1}{\delta\pi R} (a_0 h + b_0), \text{J/m}^3 (\text{N/m}^2). \quad (3.2)$$

For a pyramid or cone, the principal component of physical hardness:

$$\text{PHI}_x(\text{HB}, h) = \frac{b_v}{3\beta} \frac{1}{h} + \frac{a_v}{3\beta}, \quad (3.3)$$

a_v, b_v, β - designation of the parameters of the polynomial (1.4) for a pyramid, cone indenter.

The relationship between the function and the number of physical hardness with the empirical hardness on the Brinell scale.

In general, the formula for the empirical hardness function MKI is , for the projected contact area S_{op} [4]:

$$\text{HIM}(h) = \text{PHI}_x(\text{HB}, h) = \frac{F(h, R)}{S(h)} = \frac{F(\text{HB}, h, R)}{S_{op}}, \text{N/m}^2. \quad (3.4)$$

We transform the dimension from (3): , reducing m, we obtain the usual dimension , for (3.4).

It follows from the results of the analysis that for the case of laminar macroindentation (in this case, the shift of the diagram $F(h)$ along the axes is negligibly small $a_0 h \gg b_0$ [3]) the main component of the gradient of physical hardness of kinetic macroindentation by a sphere is the core (the main part) of the function of empirical macro surface hardness . Substituting the partial derivative $V'_0 = S_{ax}$ into (3), we obtain:

$$\text{PHI}_x(h, \text{HB}) = \frac{\partial A}{\partial V_x} = \frac{\partial A}{V'_p(h) \partial h} = \frac{\partial A}{S_{ax} \partial h} = \frac{F(h, R)}{S(h)}, \text{N/m}^2 \quad (3.5)$$

From (3.5) it follows that the main component of physical hardness, the indentation function $\text{PHI}_x(h, \text{HB})$ is the gradient of the energy flux of potential A, it per unit of surface area $S_{ax}(h) = S_{op}$. $\text{PHI}_x(h, \text{HB})$ depends on the work A performed by the indenter during the change in shape of the activated volume V , depends on the growth of the contact surface area $S_{ax}(h)$ (respectively depends on the depth h KI).

Finally, we obtain (3.6), the empirical Brinell hardness function (3.4) is equal to the main component of the gradient of the generalized volumetric power of the macroindentation potential Ax in the direction of the $x=h$ axis. Also, the Brinell hardness is the generalized rate of change of the potential Ax of the activated volume - $\partial A / \partial h$, in the direction of the x axis, divided by the conditional area of the projection of the contact surface $S_{ax}(h)$ of the indenter and the activated volume:

$$\text{PHI}_x(h, \text{HB}) = \text{HI}(h) = \frac{\partial A}{\partial V_x} = \frac{\partial A}{S_{ax} \partial h}, \text{N/m}^2, \quad (3.6)$$

Conclusion. Empirical and physical macro-hardness of a material is a twice specific indicator: 1st - energy density per unit volume and 2nd indicator - energy flow (work power flow) through a certain area of the contact surface. The full potential of the physical hardness of a material can be obtained using the operator div A. For this, it is necessary to consider the volume V_a as a vector field, which is formed by a set of elementary dipoles CHFL CWV energy. When solving problems of strength and physical macro-hardness, we use the analysis of the main component of the specific generalized power of the indentation process.

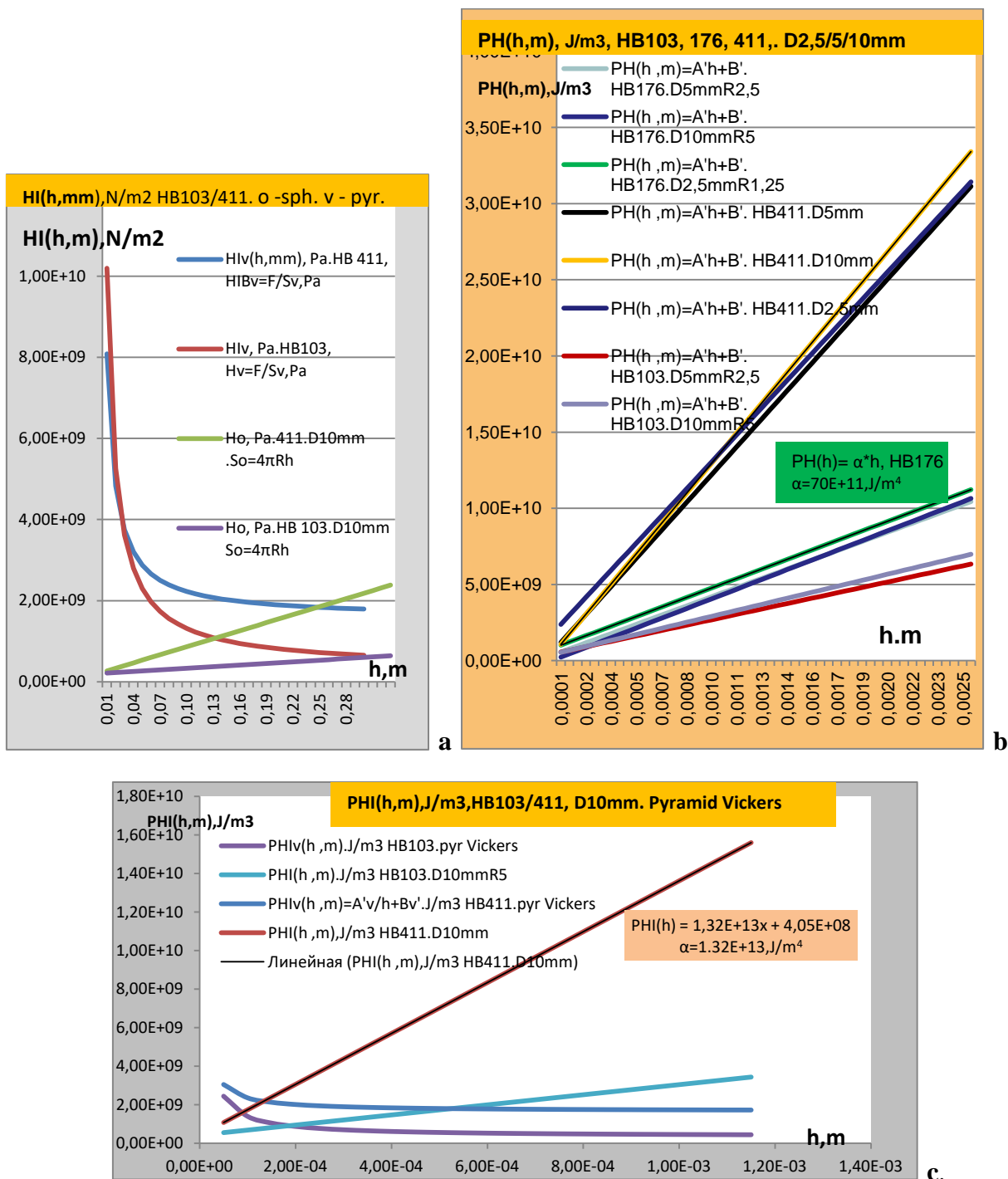


Fig.2 Diagrams of empirical HI and physical PHI hardness, Brinell units HB103/176/411[4]: a) $HI(h) = F/S$ empirical, designated HIV - Wickers pyramid, hyperbola, HIO - sphere, D10 mm, b) coincidence of diagrams of physical hardness PHI(h) obtained for D2.5/5/10 mm, constructed according to formula (3), F(h), Brinell units HB176/411, an example of a trend for HB176 $PH(h)=70E+11*h$, J/m⁴ is highlighted in green. c) physical hardness PH(h) diagrams for HB103/411, D10 and Vickers Pyramida. MKI experiments at D2.5/5/10mm (we have an invariant), Brinell sphere, test samples - HB103/176/411, formula (3), according to experimental diagrams F(h) [15].

From (12.6;12.5) it follows that with increasing depth h , for a spherical indenter, the component and simultaneously the value of the empirical macro-hardness function $HI(h)$ monotonically linearly increase. The hardness diagram confirms this property Fig.3.

Analysis of empirical standard methods for determining the hardness number (Brinell, Vickers, etc.), using the obtained theoretical physical methods showed that the empirical principles of testing the hardness number do not provide similarity, the conditions for maintaining similarity to the standard of the physical process are not met when testing with different diameters of the sphere, etc. deviations from the rule.

The standard correct process, the method of measuring hardness was used to create the first hardness scale in 1859, this is the Calvert and Johnson method (MCJ) [16]. Subsequent methods and hardness scales of Brinell, Vickers, etc., intuitively and incorrectly repeat the MCJ scale, the conditions of physical similarity of KI tests are violated. Further, this fact is confirmed by theoretical analysis of the principles of the physical process in MCJ and comparative analysis with empirical methods. The result of violations of the process standard in EH technologies is ISE.

Fig. 3a shows two diagrams $PHI_x(h, HB)$ and $HI_o(h)$ for MKI, they are obtained from (3.1) for standard hardness measures, the parameters are polynomials a_0, b_0 from (1.4), according to the published tables $F(h)$, MKI testing [15]. In this case, in the macro range of KI, the functions $PHI_x(h, HB)$ and $HI_o(h)$ coincide. This result was confirmed on different hardness measures. It was analytically proven that the measurement of the empirical hardness number according to the Brinell scale and other scales can be performed by a direct method of analyzing the $F(h)$ diagram. There is no need to measure the indenter imprint, etc. It is sufficient to apply a simple analytical calculation according to physical formulas (see Part 2.2) of the HBW hardness number according to the MKI diagram.

Conclusions.

The main part of the gradient or the main part of the component of the function of the total specific power - the component $PHI_x(h, HB)$ is a linear function, at the same time it is the empirical macro-hardness of the material $HI(h)$. Note that the hardness function is not a hardness number. It is a function of the intensity of the variable physical flow of work and the power of the waves-vortices of energy quasiparticles, which flows through the entire physical and contact surface, which covers the activated volume. Further in the text we use equivalent terms:

$PHI_x(h, HB)$ - the main component of physical hardness or the main component of generalized power MKI.

From (12.6; 12.5) it follows that for a spherical indenter, with increasing depth h , the value of the component $PHI_x(h, HB)$ monotonically linearly increases (Fig. 3 a), while the empirical macrohardness function increases. According to theory [3], a flow of increasing specific volume generalized power of energy of quasiparticles of irreversible destruction of structural bonds in the volume V_a flows through the surface S_a . In Fig. 3b, the diagrams of the main component of laminar indentation of standard measures HB176 and HB411, D2.5/5/10 mm, the nature of the diagrams confirms this property.

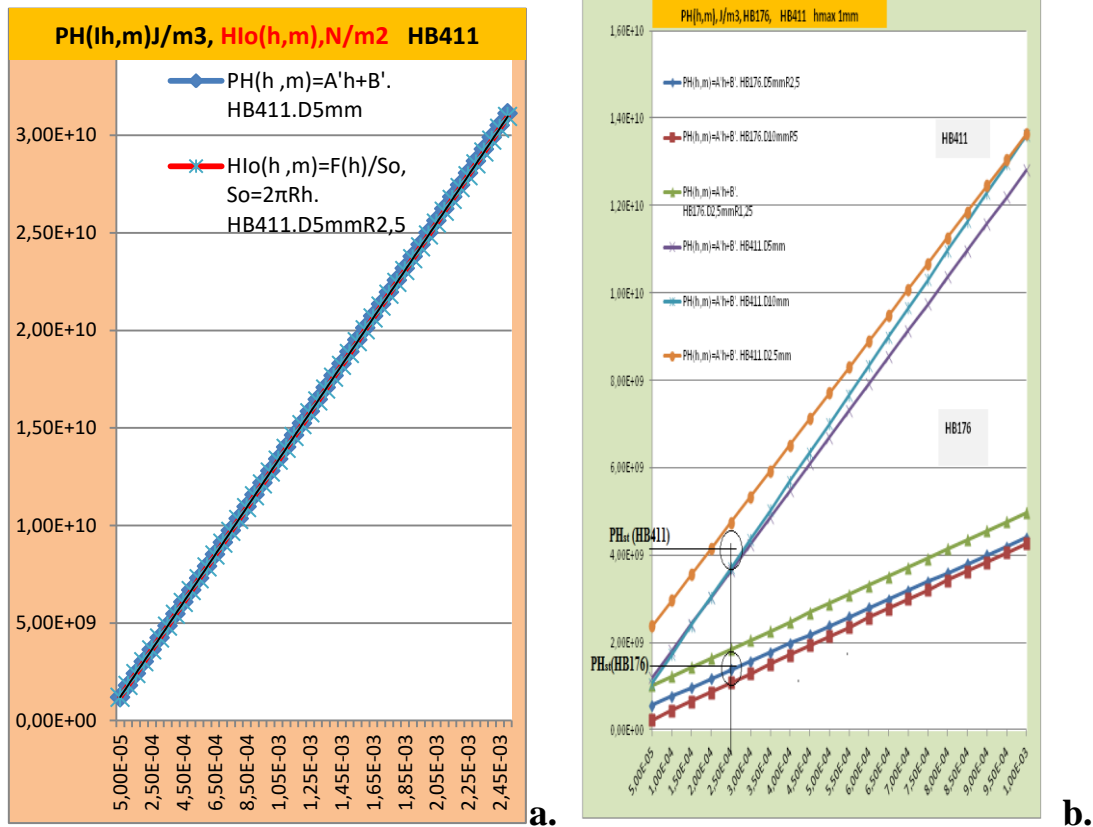


Fig.3 Coincidence of the diagram of empirical HIO and physical PHx hardness MKI, F(h) of the HB176/411 measure. a) HIO(h) = F/S empirical, sphere D5.0 mm, PHI(h) physical hardness. b) The principle of correct measurement of the number of empirical HI (h) and physical PH(h) hardness, a conditional depth standard hsti is shown, Brinell measure HB103/176/411, data in Table 2, calculations from [3].

Segment scale Indentation.

In the works [1,4], using the results of recognized MKI experiments, it was theoretically proven that if the measurement of the hardness number of different materials is performed by a sphere or a pyramid at the same maximum reference depth hsti, then these values of empirical hardness correspond to the physical principles of similarity in determining the measure of hardness (the standard of the unit of hardness). In each such case of constant depth hsti = const, all the values of the measured hardness of different materials are grouped into their own segment scale of indentation ("SSI - Segment scale Indentation"). Each SSI scale is uniquely analytically related to the basic hardness scale created in the fundamental MCJ method. The connection with the basic parameters of the MKI process is set by the same parameters of the indenter geometry and a constant ratio of the values of the depth standard hsti, etc. The basic scale of hardness measurement was substantiated experimentally in 1859 [16]. But theoretical principles for performing physical similarity during indentation were absent at that time. Using the MCJ scale, subsequent methods of measuring hardness and several scales were constructed. If we analytically perform the coordination of the parameters of the process of measuring hardness with the Brinell sphere and the MCJ truncated cone indenter (cone in this method), we will obtain an analytical relationship between the units of hardness measurement. The necessary formulas are obtained theoretically below.

The standard of macro-hardness.

To check the properties of formulas (3.4) (3.6) was used conditional standard of depth $h_{st}=0.25$ mm, considered diagrams $PHo(h, HBi)$, MKI sphere, materials of different hardness HBi . In Fig. 3b, the results of constructing functions $PH(h)$ and points of values (HBi), obtained for hardness standards HB176 and HB411 are shown. The calculation result in Table 1. As a result, it was established [3,4] that at a constant depth of all tests, example $h_{st}=0.25$ mm, the values of the function of the main component $PHoi(h_{st}, HBi)$ will be the physical number of hardness of the material (by the main component), which is obtained in physically similar test conditions. If during testing the depth standard h_{st} corresponds to the physical parameters of measuring the Brinell hardness, then equality (4) is true:

$$PHoi(h_{st}, HBi) = PHi_x(h_{st}, HBi) = PH_{ist} \approx HBi, (4)$$

In our case, the value $h_{st}=0.25$ was adopted because at this depth value the physical hardness was approximately equal to the hardness number HBW of the Brinell standard measure, on which the experimental diagram $F(h)$ was constructed by Professor V. Moshchenok [15]. Further, we will show that this depth value approximately corresponds to the point of correct physical conditions for measuring the HBW hardness (but these are not empirical requirements for the indentation, etc.).

Three lines $PHi(h, HBi)$ are plotted on one measure of hardness, at three values of sphere diameters D2.5/5/10mm/. The points of coincidence of the calculated value of PH_{st} and the nominal hardness of the measure HB are shown, they are circled. Thus, we have a hardness invariant when measuring with different sphere diameters. For MKI with different sphere diameters, on one measure of hardness, we obtain one eigenvalue of the material hardness number $PH_{st}(h_{st})$, which is approximately equal to the nominal value of the tested standard. At the point $h_{st}=0.25$, the calculated values $PH_{st}(h_{st})$ coincide with the values $HBWi$ on the Brinell scale, for different tested measures of hardness. We have only a formal discrepancy in the recording of the dimension, physical and empirical hardness. The dimension of the conditional pressure N / m^2 (empirical hardness) physical hardness J / m^3 . We can easily obtain the equality by transforming the dimension, $J/m^3 = N*m/m^3 = N/m^2$.

In this case, I selected the value of the depth h_{st} in the function $PHo(h, HBi)$ by iteration, achieving the coincidence of the values obtained by calculation and the hardness number of the tested Brinell measure itself. Next, we will show the analytical method for selecting the exact value of the depth standard h_{st} , for repetition, preserving the original scale of the correct MCJ scale. Analysis of the physical properties of the function $PHo(h, HBi)$ and the empirical function $HI(h, HBi)$ confirmed the theoretical formulas and results. To confirm and theoretically substantiate the obtained result, we will consider the physical principles, the similarity conditions created in the fundamental method of measuring the MCJ hardness.

Table 1 summarizes the results of the theoretical calculation of the conventional standard of the hardness number, based on the MKI results of standard Brinell hardness blocks, Fig.3b. The hardness was calculated for the conventional standard $h_{st} = 0.25$ mm, according to the physical diagram $PHi(h)$, block HB103/176/411. D2.5/5/10 mm. [4]. The calculation was performed using the physical method, formula (3.1), at the same reference depth $h_{st} = 0.25$ mm. The hardness values obtained for three standard blocks with different hardness levels agree

satisfactorily and repeat the proportions (ratio) of the hardness values of different blocks on the HBW scale. There were permissible deviations in the calculated hardness values and the nominal hardness values of the tested Brinell blocks. The reasons for the small discrepancies in the hardness values of the HBW standard (block) and the results of the theoretical assessment of the hardness of this block according to the KI test diagrams are discussed below.

Table 1. Results of theoretical calculation of the conventional standard of physical hardness, $h_{st} = 0.25$ mm, according to the PHI(h) diagram, measure HB103/176/411. D2.5/5/10 mm. [3].

Hardness on the HBW scale	PHS average physical hardness J/m^3	The value of the standard of physical hardness (5.2) PHS, J/m^3 , according to the diagram F(h), hardness measures HB103/167/411, diameter 10/5/2.5mm. Conventional standard $h_{st} = 0.25$ mm		
HB411	$403 \cdot 10^7$	$4,74 \cdot 10^9, (D2,5)$	$3,64 \cdot 10^9, (D5)$	$3,71 \cdot 10^9, (D10)$
HB176	$145 \cdot 10^7$	$1,85 \cdot 10^9, (D2,5)$	$1,37 \cdot 10^9, (D5)$	$1,08 \cdot 10^9, (D10)$
HB103	$105 \cdot 10^7$	$1,11 \cdot 10^9, (D2,5)$	$1,03 \cdot 10^9, (D5)$	$1,07 \cdot 10^9, (D10)$

Using formulas (3.3) and (3.1), we obtain from the function of the principal component of physical hardness $PHI_x(\sqrt{x}h, HB)$ a simplified formula (4.1) for calculating the value of a given segmental (as well as empirical HBW) hardness at a point, this function forms a series of new values of a physically correct segmental scale. At the same time, we find the number of physical hardness, on this scale, on the function. Formula (4.1) is an analytical relationship between the hardness values of an arbitrary segmental and physical hardness scale (the empirical Brinell scale is also segmental). These results are one of the options for a simple explanation of the size effect in empirical hardness testing methods.

$$HIM(h_{st}) = PHI(h_{st}) = \frac{2a_o}{\delta\pi R} h_{st} \quad h_1 < h_{st} < h_2 \quad N/m^2 \quad (4.1)$$

In Fig. 2b, the functions of the principal component of hardness are constructed on the basis of MKI test data with a sphere of different diameters for three values of standard Brinell hardness measures. In this case, we had a laminar MKI process, for the hardness function, one combined parameter can be applied to it, we have an invariant of the value of the sphere diameter D2.5/5/10mm:

$$HIo(h) = PHI_x(h, HB) = \alpha \cdot h, \quad N/m^2, \quad \alpha = \frac{2a_o}{\delta\pi R} = \text{const}, \quad N/m^3 \quad (4.2)$$

Where: $\alpha = \text{const}, N/m^3$ is a combined parameter that takes into account the indenter shape, the generalized velocity KI and hardness, a_o is the parameter of the F(H) diagram from (1.4). The $PHI_x(h)$ diagrams of physical hardness for different values of D2.5/5/10mm are invariant to the sphere diameter, this property is valid for any material hardness HBi 103/176/411. But each hardness has its own parameter a_{oi} and.

Conclusion: For values of $D > 2.5\text{mm}$, $\text{HB} > \text{HB}103$, $2a_0h \gg b_0/h$, in approximate calculations $\text{PHI}_x(V_x h, \text{HB}) = \text{HIM}(h)$, to construct the empirical hardness function, simplified formulas (4.1) and (4.2) can be used. If we have the parameter a_0 of the approximation $F(h)$ from (1.5), then formula (4.2) is applicable. Examples of graphs $\text{PHI}_x(V_x h, \text{HB})$ and analysis of the properties of the $F(h)$ diagrams in Fig. 2, 3, 4

Function of the generalized rate of change of the indentation force.

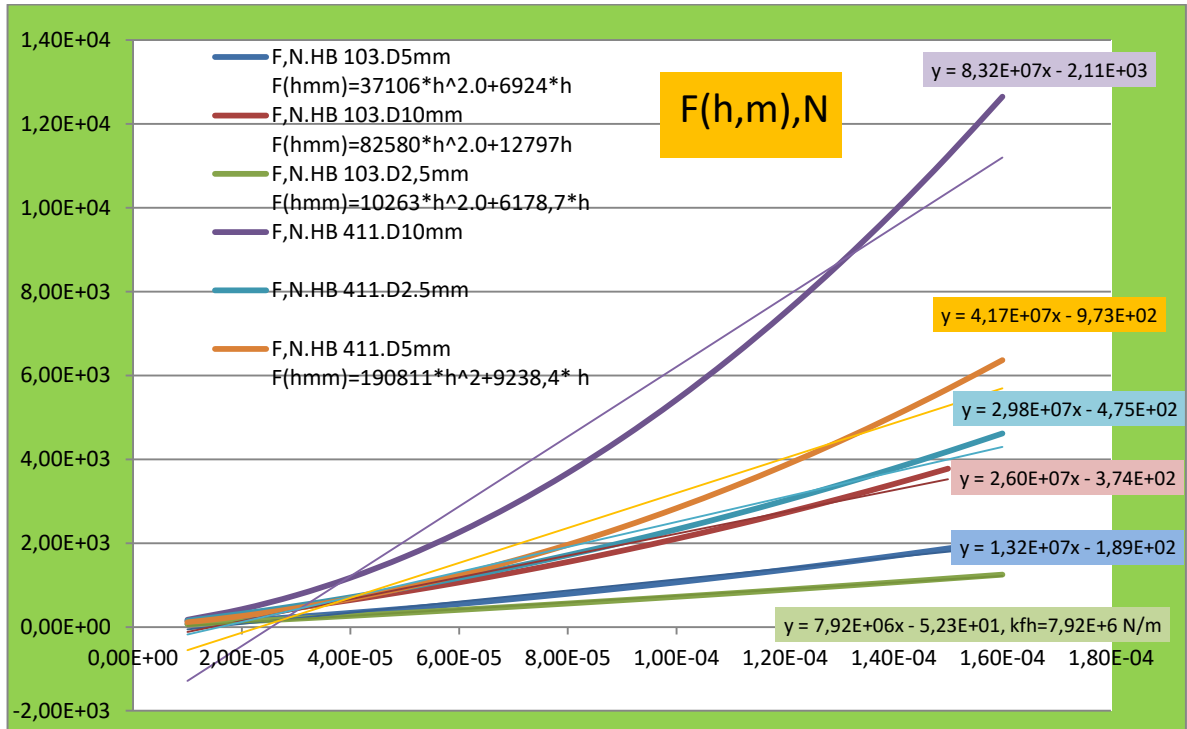


Fig.4 Analysis of $F(h)$ diagrams of MKI standard hardness test blocks HB103/411, d2.5/5/10mm, the Excel linear trend approximation method was used, the equations of the linear trend $F = kfh \cdot h + c$ are shown. Functions $F(h)$ [15]. Linear trend – constant rate of force growth $F_t' = \text{const}$.

Using (1.5) and the parameters of the function $F(h)$ of the process, we find the function of the generalized rate of force growth $k_{f_{hci}}$, where h is the generalized time of MKI:

$$k_{f_{h}}(h) = F'_h = 2a_0h + b_0 \quad (5.1)$$

Fig. 4 shows an example of a linear trend from the approximation of the MKI function $F(h)$, the parameter kfh – the generalized MKI rate, is determined for standard hardness test blocks HB103/411, d2.5/5/10mm., the calculation is performed using Excel. In this case, the functions $F(h)$ are nonlinear to varying degrees, the usual MKI method is represented by a sphere. It is obvious that with decreasing diameter of the sphere and decreasing material hardness function $F(h)$ is approximately linear. From (5.1), under condition, $2a_0h \gg b_0$ it follows:

$k_{f_{st}} = 2a_0h_{st} + b_0 \approx 2a_0h_{st} = \text{const}$. In this case we have a segment (interval) of indentation depth, $h_1 < h_{st} < h_2$ on which we obtain a linear scale of hardness. We apply a special term for this segment (interval) of indentation depth: segmental hardness scale (PH segment). On such a depth segment MKI the generalized velocity is constant and equals:

$$k_{fhs} = k_{fh}(h_{st}, a_o(HB, D)) \approx 2a_o h_{sts} \quad h_1 < h_{st} < h_2 \quad (5.2)$$

Where, k_{fhs} is the value of the parameter of the generalized velocity MKI for the case of a linear trend of the function MKI in the vicinity of a point h_{sts} inside the segment

$$h_1 < h_{sts} < h_2 .$$

Finally, for the case of a laminar process MKI of a material by a sphere, we obtain the dependence for the parameter of the linear trend k_{ifh} of the function $F(h)$ with the parameter polynomials from the function (1.4) - $a_{io}(HB_i)$, where the material of some hardness HB_i :

$$k_{ifh} = 2a_{io} h_{st} \quad h_1 < h_{st} < h_2 \quad (5.3)$$

Conclusion. For a segmental scale of hardness, it is possible to determine the characteristic parameter of the material hardness - the generalized velocity MKI - k_{fhs} (5.3). The parameter is equal to the value of the tangent of the angle of inclination of the diagram $F(h)$ at this point with an accuracy of the normalization factor, this result was experimentally confirmed in [14]. From the analysis of the properties of single-act diagrams MKI it follows that on the monotonic function $F(h)$, it is possible to obtain several scales PHS_i for different segments $h_1 < h_{i,sts} < h_2$, with a relatively linear section of the function $F(h)$. Each such section $h_1 < h_{i,sts} < h_2$ will have its own scale of hardness measurement (specific power MKI). This theoretical conclusion is confirmed by independent experimental and analytical studies of hardness properties in [19].

The conducted studies and calculations [3.4] showed that in the area with constant generalized velocity MKI, it is possible to perform a simple calculation of the value of the hardness number MKI, for example, on the Brinell scale, without using standard methods of measuring the indentation, etc. The results of the calculations and analysis of the KI diagrams confirmed the theoretical assumptions and conclusions. In particular, the analysis showed that the linearity property of the function $F(h)$ ($k_{fhc} = \text{const}$) allows us to significantly simplify the analytical calculation of the hardness number, using formulas (5.3), etc.

The linear process of increasing the force F can be ensured in different ways. For example, by choosing a special shape of the indenter (see below the MCJ method Part 2.4). The linear process of increasing the force $F(h)$ can be created, with a degree of accuracy sufficient for calculating the hardness, by a special testing machine KI. This principle of testing the hardness of a material is used in the cyclic kinetic indentation method [14].

Conclusion. If the function $F(h)$ is linear on the interval $h_* < h_{stx} < h_{max}$, then the parameter of the trend of the function $F(h)$ MKI of the material is $k_{fhci}(H_i) = \text{const}_i$, where h_* is the relaxation period of the equilibrium state in the boundary region of contact of the indenter and the material. In this case, the value of the function $PHI_x(V_x h_{stx}, H_i) = PH_{stx}$ is the value of the physical hardness of the given material on the given interval MKI. Example Part 2.5..

An example of an analytical method for calculating the material hardness number using an ideal diagram F(h), the case of MKI by a sphere $k_{fhc} = \text{const}$.

Let a process with a constant generalized indentation velocity be ensured in some way in the entire macro range of MKI $F'_h(h, R, HB_i) = k_{fhc}(h, R, HB_i) = \text{const}$, up to a depth value of h_{max} , example Fig.13a. In this case, from (3) by simple transformations when substituting the experimental value of the parameter into it $ki_{fhc}(HB_i)$, we obtain a formula that allows us to analytically obtain equation (6.), (6.1), relative to the physical hardness function $PHI_x(h, HB_i)$:

$$HBW_i = PHI_x(h_{\text{max}}, HB_i) = \frac{F(h, R)}{\delta\pi R h_{\text{max}}} = \frac{F'_h(h, R, HB_i) \cdot h_{\text{max}}}{\delta\pi R h_{\text{max}}} = \frac{ki_{fhc}(HB_i)}{\delta\pi R} = \text{const}_i \quad (6.)$$

$$HBW_i = PHI_x(h_{\text{max}}, ki_{fhc}(HB_i)) \quad (6.1)$$

$$h_{\text{max}} = \text{const}, \quad h_{\text{max}} = h_{EHi}, \quad k_{fhc}(h, R, HB_i) = \text{const}$$

Where, $ki_{fh}(h, HB_i) = F'_h(h, HB_i) = \text{const}$, is the experimental value of the generalized velocity of MKI by a sphere on the interval $h_0 - h_{\text{max}}$. In this equation, a possible option is the $h_{\text{max}} = h_{EHi}$ experimental value of the indentation depth, for which the value was calculated in the empirical method HB_i .

Another solution option. If the speed of the kinetic or single-act process MKI at the point h_{Brin} is known - the depth value (the point of measurement of the indentation according to the standard) at which it was established according to the Brinell scale, then it is possible to analytically switch to the correct physical hardness number of this material in sphere tests. Details on this method are in a separate article. value of the empirical hardness of the material

Thus, if the conditions of physical similarity are not met during hardness testing by the empirical method, then an incorrect scale will be formed. Formally, it is possible to select the depth and other parameters, copying only the absolute values of Brinell hardness. But in this case we will receive a segmented, related scale, analytically related to the scale and the hardness number MCJ. For a strictly correct correspondence between the Brinell scale and the MCJ scale, it is necessary to meet all physical conditions of similarity during testing. These requirements are considered in Part 2.4.

Finally, from (6) for a sphere indenter, the main component of physical hardness is equal to the product of the linear trend parameter $ki_{fhc}(HB_i)$ and the shape parameter α_{PHI} :

$$HI\alpha(h) = PHS_i = PHI_x(h) = \alpha_{PHI} ki_{fhc}(HB_i) = \text{const}_i \quad \alpha_{PHI} = \frac{1}{\delta\pi R} \quad (6.2)$$

Where, $\alpha_{PHI} = \frac{1}{\delta\pi R}$ is the indenter shape parameter for MKI. $\alpha_{PHI} = \frac{1}{\delta\pi R}$ is the linear trend constant of the experimental diagram F(h) for MKI of a material with hardness HB_i . This case is

shown in Fig. 3a, the hardness functions are: $H_{oi}(h) = PHS_1 = PHI_x$, α_{PHI} is the constant of the MKI process for this material if the function $F(h)$ is linear in the considered section. For different material hardnesses, we obtain a fan of linear non-intersecting diagrams (rays) under MKI conditions by a sphere, Fig. 12c. Each ray - diagram $PHI(h)$ has its own parameter. The intersection points of the rays $PHI(h)$ with the abscissa h_{sti} form their own correct hardness scale under these MKI conditions.

Discussion of item 2.2

With different values of the single-act MKI process (- the point of measurement of the indentation, etc.), we obtain different scales of the empirical hardness $H_{oi}(h)$ measurement scales and different ratios with the physical hardness scale PHI (h_{max}). For complete similarity in hardness measurements, it is necessary to maintain the standard of the MKI process, which was developed by Calvert, Johnson [16], more details on it below. Using the formulas of the theory, we can analytically find the value of h_{sts} , which will provide the correct scale of hardness values on the Brinell scale (an approximate similarity of the scale with the MCJ scale is achieved). For this, we apply equation (6). We set the already known or determine from the existing MKI process the experimental parameters of the approximation by the polynomial a_o , b_o , (1.4) for the function $F_{exp}(h)$ obtained during tests of the standard Brinell measure with a sphere. Substituting into (6) the values of the required hardness HBW (for example, the standard measure) and the parameters a_o , b_o , we obtain an equation for calculating the depth standard h_{sts} :

$$HBW = \frac{1}{\delta\pi R} (a_o h_{sts} + b_o), J/m^3 (N/m^2). \quad (6.3)$$

If we use the h_{sts} value - the MKI depth standard - in testing, then when measuring the hardness of a certain material with different D spheres, the physical conditions for similarity of measurements on the HBW scale will be met. In this case, there is no need to measure the imprint, it is enough to determine the force at a given point $F(h_{sts})$ and apply formula (3.4), we obtain the desired hardness number. Using (6.3), h_{sts} and parameters a_o , b_o , we also find the HBW hardness value on the Brinell scale in a simplified manner.

Table 2 contains the results of calculating the hardness values = $PHI_x(h_{sts})$ in different MKI technologies, which show the nature of the influence of the h_{max} value (the hardness calculation point). Results of theoretical evaluation of the physical parameters of hardness MKI sphere D2.5mm: the value of physical hardness $PHI_x, J/m^3$, (5.2) according to the $F(h)$ diagram obtained on hardness measures HB103/411 and steel C45. Conventional depth standard KI in calculations $h_{st} = 0.25mm$.

For the function $F(h)$ of a single-act process, formulas (3.1 and 3.6) were used in the calculations. For the analysis of the single-act diagrams $F(h)$ of standard hardness tests MKI HB103/176/411 Fig. 4, the Excel program was used. The single-act diagram for steel C45, Fig. 9 data [20]. The cyclic diagram Fig. 6 [14]. The maximum depth of the single-act process is designated as h_{iact} . For the cyclic process, further in the text the designations and discussion of the calculation results for different functions $F(h)$ MKI, experimental [17] are used. Designations of the parameter of the generalized velocity MKI for different types of force

diagrams F(h): - generalized velocity F(h) of a single-act MKI, k_{fhc} - consolidated (equivalent) velocity for the cyclic function Fcycl (h) MKI.

Table 2. Results of theoretical calculation of PHS, k_{fh} , MKI process with D2.5mm sphere, experimental functions F(h), single-act MKI, standard hardness measures HB103/176/411. Cyclic MKI steel C45.

Material	Hardness, ISO HBW, Pa	PHS = $PHI_x(h_{sts})$, Pa (N/m ²)	$k_{fh}=dF/dh$, N/m D2,5 mm	conclusion
1	2	3	4	5
HB411 $t_{iact} = 5-10sec$	$411 \cdot 10^7$	$296 \cdot 10^7$ $h_{iact} = 0.15mm$	$2,98 \cdot 10^7$	Low hardness *
HB103 $t_{iact} = 5-10sec$	$103 \cdot 10^7$	$34 \cdot 10^7$ $h_{iact} = 0.15mm$	$0,79 \cdot 10^7$	Low hardness *
C45, KI_{iact} $t_{iact} = 5-10sec$	$184 \cdot 10^7$	$68 \cdot 10^7$ $h_{iact} = 0,12mm$	$1,21 \cdot 10^7$	Low ** hardness
KI_{cycle}	HBW, Pa	PHC = $PHI_x(h_{icycl})$	$k_{fhcycl}=dF_{cycl}/dh$, N/m	-----
C45 $t_{cycle} \approx 1600sec$	$184 \cdot 10^7$	$185 \cdot 10^7$ $h_{icycl} = 0.25mm$	$1,84 \cdot 10^7$	*** sample hardness

MKI parameters to Table 2: sphere D2.5mm:* [15]; ** $h_{iact} = 0.12mm$ [20] ; *** - $h_{pl}=h_{\Sigma cycle} =0.25m$ [14].

Thus, it can be reasonably assumed that in the general case, segmental hardness has only partial similarity to the physical root method and the MCJ material hardness measurement scale. In order for the functions of empirical and physical hardness, $EH(HBi)= PHI(HBi)$, to fully coincide, the numbers and dimensions must be preserved (hardness measure), all physical conditions of the MKI - MCJ standard process must be repeated, more details on this in Part 2.4.

Example: comparison of volume sizes in quarts or gallons will be correct if you indicate whose measure, English or American, and indicate the method of converting them to the universal measure of volume of the SI system, etc.

If we ignore the existence of different principles for determining the volume measure (with the same name, but without specifying the principle of measurement, English or American), then we can get a "size effect" in the measurements.

Table 2 shows the results of calculating the values of the standard hardness of the material on the Brinell scale, using the physical method of analyzing the $PHI_x(h)$ function. Analysis of the results of this calculation method showed that in standard methods, formulas, coefficients, etc. are intuitively selected for the "mechanical" repetition of the values of the hardness number of different materials in the experimental Calvert and Johnson scale (the first test table). In the

standard methods of Brinell, Rockwell, etc., the process of selecting a point (parameters) for measuring hardness occurs without theoretical justification and analysis of the standard physical process of MCJ tests, while there is no similarity of the physical processes of measuring the hardness number.

Conclusion.

From the results of the analysis and comparison of the dependencies of the physical theory and empirical methods for determining the hardness of materials, it follows that in empirical hardness, the methods are based on the mechanical selection of a combination of actions, the purpose of which is to obtain a formally previously approved standard - the hardness number. In practice, this is achieved by choosing the depth h , varying the formulas for calculating the indentation parameters, etc. Such an approximate empirical method for measuring physical hardness became possible because it fully satisfied the pragmatic problems of materials science. Empirical one-act methods quite simply find the depth, force, contact area, etc., in order to obtain the formally sought number - the standard of empirical hardness and then compare the hardness in the process of solving problems of metallurgy, materials science, etc. In this process of comparing hardness numbers, there is no need for a theoretical justification of the physical principles of similarity, etc. But this approach is not applicable to solving problems of strength, durability, fatigue, analysis of the state of damage to the material, etc.

It is possible to analytically transform the experimental function and the number of empirical hardness obtained by the Brinell method (sphere) into the function and number of physical hardness. To do this, it is necessary to have all the parameters of the Brinell hardness number tests, analytically construct (restore) the experimental diagram $F(h)$ by which the HBW value was empirically determined. Theoretical formulas can be used to convert the number on the Brinell scale into the value of physical hardness and then obtain the hardness in a different specified scale, etc. To "convert" the function and the hardness value obtained for indenters of different shapes and scales, the corresponding dependencies were analytically obtained [4]. Modern empirical (standard) methods for measuring macro hardness (sphere and pyramid) are oriented toward the first experimental empirical hardness scale MCJ. But the basis of modern scales and new utilitarian methods for measuring hardness was the method, the MCJ scale.

2.3 Analysis of the principal component of physical hardness PHIX using parametric rheological functions MKI. The case of a constant generalized growth rate of the indentation force F(h)..

Let us consider the properties of the function of the principal component of physical hardness under the condition that the main quantities MKI are given as parametric functions of time t : $A(t)$, $V(t)$.

From the usual properties of parametric functions we have:

$$\frac{dY}{dX} = \frac{Y'}{X'} , \quad \Gamma_{де}, Y' = \frac{\partial Y(t)}{\partial t} , X' = \frac{\partial X(t)}{\partial t} \quad (9)$$

From (3),(9), using the parametric functions of the MKI process: $Y(t) = A(t)$, $X(t) = V(t)$, m^3 , t is the parameter, $x = h$, we find the dependence of the physical hardness function on time:

Из (3),(9), применяя параметрические функции процесса МКІ: $Y(t) = A(t)$, $X(t) = V(t)$, m^3 , t – параметр, $x = h$, найдем зависимость функции физической твердости от времени:

$$PHI_x(A(t), V(t)) = PHI_x(t, H, Di) = \frac{dA_x}{dV_x} = \frac{A'_h(t)}{V'_h(t)}, N/m^2, \quad (9.1)$$

We use the dependence for the energy potential $A(h)$ of the activated volume (1.3):

$$A(h) = \int_0^{h_{max}} F(h)dh \quad (9.1.1)$$

Suppose that we have somehow ensured that the MKI condition is satisfied:

$$k_{fh}(h, H) = F'_h(h) = \partial F / \partial h = \text{const}, N/m \quad (9.2)$$

$k_{fh}(h, H)$ – constant, generalized growth rate $F(h)$ for a material with hardness H (H is designated here as a conventional unit of hardness), the shape of the indenter is constant (example Fig. 4, Fig. 9).

Let us have $v_{RhC}(h, t) = h' = x' = \partial h / \partial t \approx h_{max} / t_{max}$, - the average constant rheological speed of movement of the indenter on the interval t_{max} , as a result we obtain:

$$h = v_{RhC} t, \quad v_{RhC} = h_{max} / t_{max} \quad (9.3)$$

We will further confirm the possibility of fulfilling such conditions by experiments.

From (9.1.1) using formula (9.3) and replacing variables, we obtain the parametric function $A(t)$:

$$A(t) = \int_0^{t_x} k_{fh}(h, H) \cdot v_{hiC} t dt = \frac{k_{fh}(h, H) \cdot v_{RhC}^2 t^2}{2} \quad (9.4)$$

$$\text{From (9.4) we find the derivative: } A'(t) = k_{fh}(h, H) \cdot v_{RhC}^2 t_{max}, J/s \quad (9.5)$$

$$V_{xo}(h) = \pi R h^2 = \pi R \cdot (v_{RhC} \cdot t)^2 \quad \text{Variant of the refined formula [4]- } V_{xo}(h) = \delta R h^2$$

$$\text{Let's find the derivative } V'_i(t) = 2\pi R v_{RhC}^2 \cdot t. \text{ Где, } 2\pi R v_{RhC}^2 = \text{const}. \quad (9.6)$$

Using (9.1), (9.5), (9.6), we obtain a function for calculating the number $PHoi$ of physical hardness of a material for MKI with a sphere of diameter Di for some arbitrarily specified indenter movement speed v_{hiC} (new speed standard):

$$PHoi(t, H, Di) = \frac{A'_h(t)}{V'_h(t)} = \frac{k_{fh}(h, H_i) \cdot v_{hiC}^2 t}{2\pi R i v_{RhC}^2 \cdot t} = \frac{k_{fh}(h, H_i)}{2\pi R i}, J / m^3$$

$$\mathbf{PHoi}(t, \mathbf{H}, \mathbf{Di}) = \frac{k_{fh}(h, H)}{2\pi Ri} \text{ J/m}^3, \quad v_{RhC} = \text{const}, \text{ m/s.} \quad (9.7)$$

Where, $\mathbf{PHoi} = \frac{k_{fh}(h, Hi)}{2\pi Ri} = \text{const}$ is a constant value for a given material with a conventional hardness of "Hi". In this MK I process, constant parameters were set: sphere Ri, is a constant rheological growth rate of force F from the indenter movement, for a given material, at $v_{RhC} = \text{const}, T^{\circ}\text{K} = \text{const}$.

Formula (9.7), obtained from the parametric functions of the MKI process, coincides with (5), which was obtained independently from (3) earlier.

Special case (9.7). If, during MKI, the sphere sets the standard of the rheological velocity of the indenter movement $v_{Rh} = \Delta h_i / \Delta t_i, \text{ m/s} = \bar{v}_{RhCJ} = 1,8\text{mkm/sec}$, this is the speed during the formation of the first physical hardness scale MCJ, then we obtain the formula for calculating the hardness number on the Brinell scale:

$$\mathbf{HBWi} = \mathbf{PHoi} = \frac{k_{fh}(h, Hi, \bar{v}_{RhCJ})}{2\pi Ri} \text{ J/m}^3, \quad (9.8)$$

Where, $\bar{v}_{RhCJ} = 1.8\text{mkm/sec}$, is the MCJ constant, see Part 2.4.

Conclusion.

From (9.7), (6.1) it follows that if a constant generalized velocity is specified for MKI of different materials - $k_{fh}(h, H)$ (6.3), then the value of the function is equal to the hardness of each material in a physically correct scale. Hardness in this case is directly proportional to the generalized velocity $k_{fh}(h, H)$, the scale of the scale in this case depends on the specific value \bar{v}_{RhCJ} . In this case, the indenter macrosphere can be of arbitrary diameter, the hardness is invariant to the value of the diameter of the macrosphere D, Fig. 3. If the value of the velocity parameter MKI sphere is equal $\bar{v}_{RhCJ} = 1,8\text{mkm/sec} = \text{const}$, then during testing we will obtain (approximately) the hardness number of the material on the Brinell scale - (9.8).

If the MKI process is performed at some constant speed v_{hRC} , and some unique constant value of the indentation depth h_{xst} is assigned, then the value of the function \mathbf{PHoi} when testing a material with some conventional hardness \mathbf{HXi} will be equal to the hardness of this material in the new scale "HX" (thus, a new measure is assigned, a new unit of measurement of the specific power of the indentation process):

$$\mathbf{PHoi} = \mathbf{HXi}, \quad \mathbf{PHoi}(h_{xst}, \mathbf{HXi}) = \mathbf{PHXsti} \quad (9.9)$$

The case of a constant generalized growth rate of the indentation force F(h).

Let us calculate the generalized velocity $k_{fh}(h, H)$ using parametric functions or rheological velocities of the MKI process. The rheological average velocity of force $v_{Rf}(h, t)$

growth is , the rheological average velocity of indenter movement is $v_{RhC}(h, t)$, (9.3). As an example, using the fundamental method of measuring hardness MCJ, we will analyze the MKI diagram using rheological functions, $F_{cj}(h)$ Fig. 5-6. Part 2.4.

$$v_{Rf}(h, t) = F'_t(h) = \frac{dF}{dt} \approx \Delta F / \Delta t = F_{max} / t_{max} \cdot t_{max} = \text{const, Hi, N/s} \quad \text{N/s} \quad (9.10)$$

Where, F_{max} is the maximum force, constant for a given material in MCJ.

$$v_{Rh}(h, t) = h' = x' = \partial h / \partial t \approx \Delta h_{max} / \Delta t_{max} = \text{const, MCJ, m/s} \quad (9.11)$$

Where, $v_{hi}(h, t)$ is the constant average velocity of MKI for any material in MCJ.

Using formulas (9.10), (9.11), parametric functions, we obtain the formula for the generalized velocity of MKI for a sphere or other indenter shape without a sharp tip:

$$k_{fh}(h, H) = \frac{v_{Rf}(h, t)}{v_{Rh}(h, t)}, \text{N/m} \quad (9.12)$$

Using rheological formulas (9.10), (9.11) we will calculate the number of physical hardness of the material in the MCJ experiments, a truncated cone indenter was used, Fig. 12b, 13a. $PHI_{iMCJ}(h)$ - the function of physical hardness in the MCJ method,

$$PHI_{iMCJ}(h_{max}) = PHI_{max}(t_{max}) = \frac{\bar{v}_{Rf}}{\bar{S}} t_{max} \text{N/m}^2 \quad (9.13)$$

$$PHI_{iMCJ}(h_{max}) = PHI_{max}(t_{max}) = \frac{F_{max} t_{max}}{t_{max} \bar{S}} = \frac{F_{max}}{\bar{S}}, \quad (9.14)$$

Where, PH_{cj} the number of physical hardness of the material in the MCJ method,

$PHI_{max}(t_{max})$ is the function of physical hardness MCJ in the rheological version (from time), $h = h(t)$.

\bar{S} - the average cross-section of the contact of the indenter and the material in the depth interval h_{max} .

Discussion.

Deviation from the standard time t_{st} during MKI hardness tests leads to a change in the scale scale, the measure of the standard - the unit of power of irreversible processes - changes, the parameters of the physical conditions of similarity of the MKI process change. A similar situation is known in standard empirical methods of hardness measurement. In cases of changing the depth h_{max} (transfer of the point of calculating the hardness number by the indentation) means an uncontrolled deviation from the standard t_{st} . In simple one-act MKI there is no exact data on the speed $v_{hi}(h, t)$, there is no function $h(t)$. In modern KI machines, these parameters are fixed, for solving other problems, etc. Trivial data on the MKI process are not enough for physical analysis and control of the similarity of hardness measurement processes. Modern empirical methods ignore the important role of the physical criterion - the similarity of the time standard t_{st} when measuring hardness, the influence of this factor is traditionally simplified as ISE, etc. Further, using examples of analytical analysis of MKI, we will consider the influence of

other physical parameters on hardness and the conditions for constructing a correct physical scale.

Conclusion.

If MKI provides a constant generalized rate of force growth $k_{\text{fn}}(h, H)$, then the value of the measure of the unit of physical and empirical macro-hardness is proportional to the generalized rate $k_{\text{fn}}(h, H)$. The scale of the hardness scale depends on the rate $k_{\text{fn}}(h, H)$. To maintain a constant scale of the scale, during single-act tests of materials of different hardness, it is necessary to establish a test time standard t_{st} and an indentation depth standard h_{st} . In this case, a constant measure of hardness is a constant unit of measurement of the specific power KI .

From (9.12) it follows that the duration of the indentation time t_{st} in MKI does not affect the value of the ratio of rheological rates: $k_{\text{fn}}(h, H) = \text{const}$, if the values (9.10), (9.11) are unchanged when testing materials of different hardness, then their ratio is also constant.

For example, in the root method of measuring macrohardness MCJ, the main parameters (9.10), (9.11) were constant, as a result of which the first physically correct scale was created, for more details see Part 2.5. During cyclic tests of MKI, these requirements are automatically maintained in each of the subsequent successive cycles, while the main characteristic of the material is maintained constant $k_{\text{fn}}(h, H) = \text{const}$. Such a process is similar to performing a series of new single-act tests of the material with equal Δh_i at each cycle. In this case, there are features of the generation of power of irreversible processes (PHIcycle), the influence of which can presumably be neglected in the first approximation. About this in the next article.