Kinetic indentation of material, function, number, universal physical unit of macrohardness.

Shtyrov Nikolay

Nikolayev, Ukraine, +380675102044, E-mail: nasht@ukr.net

Abstract:

Three directions of development of instrumental indentation. Physical energy analysis of the force diagram of indentation according to ISO 14577. Physical model of the process of kinetic macroindentation of a material, macrohardness criterion, thermomechanical potential, state function. The value of the standard of the kinetic physical hardness of the material. Relationship between empirical and physical macrohardness of a material. The reason for the size effect is in standard macro indentation methods. Physical standard of material macrohardness during kinetic indentation by a sphere. Features of the Calvert-Johnson hardness measurement method. Universal physical unit of macrohardness of kinetic indentation.

Key words: review, physical theory of kinetic indentation, method of determination, function, number, universal unit of physical macrohardness of a material, ratio of standard and physical macrohardness.

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Part 1.

Physical macrohardness of the kinetic indentation of the material. Function and universal unit of measure.

1. Three directions of development of indentation. Physical concept of hardness and strength of a material. Review, conclusion.

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

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

We briefly characterize the features and disadvantages of each direction, relying on the physical principles of the analysis of the indentation process, and draw conclusions.

Single empirical indentation of macrosurfaces.

Initially, the concept of hardness is a mechanical characteristic of a material, closely related to the concept of strength. The first, physically correct method of measuring hardness, according to studies [1], was created by Calvert-Johnson (1859) [2]. The authors were the first to use a truncated cone indenter in tests. A unified scale of hardness of materials from lead to cast iron, etc. has been created. Theoretical physical determination of hardness by the Calvert-Johnson method (hereinafter referred to as MCJ) has not been carried out. The analysis of this method [1] showed that it constitutes the key physical principle of macroinstrumental indentation. For more than forty years this method has been unchanged. Over the next hundred years, new methods of indentation emerged. They periodically changed the methods of data processing of the mechanical act, empirical methods for processing the final parameters of the act of indentation. These changes imperceptibly overshadowed the fundamental physical principle of indirect comparison of different specific energy, power of the physical process of indentation of materials of different hardness. The changes affected only the methodological and technological methods of measuring and processing external, empirical data. At the same time, the original dimensionless comparative hardness scale MCJ was retained, the list of materials, nomenclature and method for analyzing the indentation process were expanded. There are contradictions in the provisions of the modern generally accepted "mechanical" interpretation of the concept of material hardness [3]. Engineering discoveries in the field of new methods for determining the dimensionless hardness number have overshadowed the fundamental physical principle of comparing various physical and mechanical properties of the indentation process. In practice, the following canonical definition has been fixed (abbreviated). 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 [3]. Further, we use this definition as a recognized formulation of the concept of empirical hardness - EH (Empirical Hardness). By this designation we mean the methods of one-stage macro-surface empirical indentation. Instrumental indentation is considered separately.

EH methods are widely and successfully used in industrial and scientific studies of the hardness properties of alloys and other materials. Let us consider three well-known methods: Brinell (indenter sphere), Rockwell (sphere and sphere-cone), Vickers (pyramid), etc. A detailed review of the methods can be found in [3]. Summarizing the conclusions of the monograph by Professor V.I. Moschenok of an indentation specialist and own research [1], we will discuss the characteristic shortcomings of the empirical methods of one-stage and kinetic indentation. Brinell method. The calculation of the hardness number, within the framework of ISO 14577-1:2002 [4], causes difficulties in choosing the correct scale, in which an empirical relationship between force and hardness is established. There is no reasonable clear selection criterion. The scale for measurements (table) was obtained empirically, is formed empirically, depends on the force and shape of the indenter, etc. There are more than thirty scales for measuring hardness in the method. Thus, the hardness number depends on the force, but this dependence, in the general case, does not have a systemic character. The American standard for this method of indentation suggests the use of additional scales, thereby further complicating the method. The choice of the desired scale is a complex and ambiguous and often contradictory system. This method, or similar to it, does not register the resistance of the metal to penetration, but the end result of the process. This method contradicts the original definition of EH. The Brinell

method works stably in the region of large loads. For micro and nano loads, its application is problematic and requires additional study and improvement [3].

The Rockwell method is widely used in practice. In fact, the method does not correspond to the essence of the above definition of EH hardness. The hardness number does not correspond to the numbers of other methods, it is devoid of any physical meaning [3]. Vickers hardness is regulated by four standards, in which there is a significant difference in the choice of the required force during measurements, a complex system of comparison and designation of results. A particularly confusing situation manifested itself in the micro range, where the dependence of hardness on load (effect - ISE) is observed [3]. The method has some disadvantages inherent in EH indentation [3]. Analysis and review of one-act and combined macro methods of empirical hardness can be found in [1, 3].

Macro instrumented indentation (kinetic indentation).

Methods of instrumented indentation appeared around 60-70s. Kinetic, instrumented indentation is a highly informative method for studying various material properties and the physical process, compared to the single-stage EH method for measuring hardness. The ISO 14577-1:2002 standard [4] defines: the work of the indentation process, the modulus of elasticity EIT, the indentation creep CIT, the indentation relaxation RIT, the plastic and elastic components of the indentation work. In the kinetic method according to the ISO 14577 standard, the hardness number of the HM material is determined by Martens. HM hardness depends on the load on the indenter; this property of the hardness number is called the indentation size effect. The standard provides for the construction of the force function on the indenter F(h), example Fig.1b. The choice of the value of the maximum force F, when measuring surface or bulk hardness [3], is also ambiguous, empirical in nature [1,3]. The function F(h) and the hardness number are affected by the shape of the indenter. However, there is no strict connection. For a spherical indenter, with increasing load, the hardness increases - reverse indentation size effect; for an indenter in the form of a Vickers or Berkovich pyramid, with increasing load, the hardness decreases - a direct or simply dimensional effect (indentation size effect); for a sphero-conical indenter, mixed effects arise. [1,3]. The advantage of the instrumental method of indentation is that there is no need to measure the imprint size. Energy and other indicators of the indentation process in the ISO 14577 standard have significantly expanded the volume and depth of controlled information. But the standard initially lacks a reasonable physical criterion of hardness. Therefore, the correct method of comparing different empirical methods, scales, hardness numbers cannot be implemented. Contact pressure or conditional stress, which, explicitly or implicitly, is present in any empirical hardness indicator, is not an unambiguous physical characteristic of the state of the considered thermomechanical system tool - material - machine [1]. In standard algorithms for calculating the hardness number, the shortcomings of the canonical definition of EH appear. The "mechanical", empirical formulation of the concept of hardness is retained. There is no connection between the kinetic physical parameters of the indentation process and the energy characteristics of the internal process of material transformation, there is no explanation for the cause of the harmful size effect, etc. The concept of EH is within the framework of the theory of continuum, the theory of elasticity, and the mechanics of a deformed solid body. Irreversible changes in a solid during indenation are considered phenomenologically and empirically. In ISO 14577, the determination of the hardness number of a material is dominated by empirical principles. In standard methods, there is no physical criterion for hardness as a process. We need it to estimate and compare the specific energy of the internal irreversible structural-energy kinetic processes in materials of different hardness. The standard provides an estimate of the absolute value of the indentation energy. From the point of view of physical theory, this is not enough to objectively characterize the state of a macroscopic thermomechanical system in materials with different hardness properties during instrumented indentation.

Nano-micro instrumented indentation.

The use of new technologies of nanomaterials and coatings, the creation of high-precision devices and mechanisms forms an independent direction of nano and micro instrumented indentation. This direction is more focused on the study of the properties and structure of the fine structure of materials, the features of the upper nano-micro layer of the material or its coating. In materials science, technologies of nano-micro design of materials and thin coatings, microhardness provides information on the properties of phases and structural components [1,5,6]. An analysis of some scientific results of the development of this direction of instrumented indentation can be found in [1,3,5,6,7].

A comparative analysis of the values of the material hardness number in the nano and macro ranges shows that the physical energy nanohardness is more than ten times greater than the empirical macrohardness [1]. In nanoindentation, this experimental fact is bypassed by the formal methodological method of selecting the “refined” contact area, justified by the “size effect”, etc. The use of the concept of the geometric contact surface of the indenter and material in the nanorange as a characteristic of internal processes is rough and incorrect [1]. In the active volume of contact between the material and the indenter, nano-interaction of bodies occurs at a high physical energy level, the specific power of the processes and the mechanism of irreversible changes in the nano-activated volume is characterized by other equations and dependencies [1, 5]

The ISO 14577 standard uses elements of the physical analysis of the kinetic indentation force diagram. In particular, in the method of Oliver and Farr, the contact stiffness parameter is used to correct the value of the hardness number. The standard does not contain a physical substantiation of the formula for this parameter, it is a

phenomenological approach. The conducted studies have shown [1] that this parameter has a physical basis, thereby confirming some of our theoretical results.

An analysis of the experimental specific energy parameters of material transformations [1,3,5,6] in the nano-micro-dentation range showed that this process has a specific power (J/m3) 1–2 orders of magnitude higher than in the macro range. With an increase in the force and depth of CI by a sharp indenter (pyramid, cone, etc.), a combined kinetic process is formed. There are two physical mechanisms of transformation of the fine structure and volume of the material with different specific power of release and transmission of energy. To form the criterion and theory of nanophysical hardness, we first establish the concept of macrophysical hardness of the instrumented indentation process. This theoretical base will allow us to perform a physical analysis of complex nano-micro-macro kinetic processes [1].

Conclusion.

Currently, there are a number of standards and methods, scales that do not have a reasonable systematization, there is no single way to correctly compare different measurements of hardness. There is no physically theoretically substantiated definition of hardness. In general, we will define the existing approach as the empirical hardness of the material EH (Empirical Hardness). Hardness values obtained by EH methods have no physical content and are not correctly comparable. A similar situation applies to scratching methods [3,5]. In EH, correlation parameters are determined by different methods and tools, which were historically called the hardness number of the material.

The physical basis for determining the hardness number was used in the method of Calvert Johnson (1858, hereinafter MCJ). On its basis, the first generalized energy scale of systematized values of hardness of different materials was obtained, it is built on physical principles. The method was based on a strict principle of similarity in testing materials of different hardness. After forty years of use, the MCJ has been corrupted by various additions. The (partially) original scale for correct comparison of hardness was retained. As a consequence, the empirical single-act method for measuring the hardness number was established. For solving applied problems of materials science, metallurgy, mechanics, etc., the EH methods are acceptable. Systematization, generalization and development of EH methods without physical justification has no prospects. Building a theory of kinetic indentation and substantiating the physical unit of hardness, creating a base for a single measurement standard and correct comparison of hardness numbers from different methods and ranges is impossible within the framework of the EH. For the development and improvement of indentation methods, it is necessary to create a basis - the physical theory of hardness.

Physical concept of hardness and strength of a material.

Hardness and strength are closely related physical and mechanical characteristics of the material. Both concepts are inextricably linked with large plastic deformations and high energy density of the material during tests for ultimate strength characteristics. ISO/TR 29381:2008 provides a method for evaluating the tensile strength parameter. An example of an empirical formula relating Brinell hardness and ultimate tensile strength: $HB = 3\sigma_B$, where σ_B - is the ultimate tensile strength of the material. Simple formulas are used by metallurgical engineers, metallurgists, technologists, strength specialists, etc.

The emergence of new structural materials, technologies for applying thin coatings, and methods for hardening the surface of solids initiated the development of new methods, tools, and equipment for indentation. Methods for mechanical testing of materials on macro samples are laborious, costly, and often inaccessible. Establishing a physical and analytical relationship between hardness and mechanical strength of a material is an urgent engineering and scientific problem [3,5,7].

The accumulated experimental data indicate that during indentation and mechanical testing, there are largely common physical mechanisms and processes for the conversion of different energies scattered in the fine structure of the macrovolume of the activated material. The final result of empirical measurements is expressed as the value of some external (empirical) process parameter - the hardness number or the value of the tensile strength (yield, fatigue, etc.). The physical theory of hardness considers the parameters and properties of the kinetic testing process (indentation, tension, etc.). To characterize the process of kinetic indentation of a material, we use: the rate of increase in the energy density of the activated volume (specific generalized indentation power), the rate of increase in force, the function of shape change or the specific formed surface, etc. These are the kinetic characteristics of the process of interaction between the material and the tool as part of the entire system.

The concept of physical kinetic hardness.

The theory of physical hardness uses the principles of the physical structural-energy kinetic theory of the strength of destruction and deformation of solids [1,8,9,10]. Physical strength - the ability of a material to maintain for a certain period of time, to lose at a certain speed and power its original properties, parameters under the rheological action of various physical and mechanical factors or loads: temperature, stress, time, radiation, hydrogen potential, etc. Physical kinetic hardness, in this context, is a particular case of the physical process of shaping and irreversible structural transformations of a deformed solid body under the influence of a moving indenter. An experimental-analytical physical method for analyzing kinetic indentation data consists in constructing a physical hardness function and determining the number (value) of the physical hardness of a material. These are objective individual integral characteristics of the process occurring in a deformable, indentable material as part of a certain

thermomechanical system or certain physical and mechanical test conditions. The kinetic indentation method combines the general physical methods of the theory of strength and durability of materials; this is a special case of the physical mechanics of reversible and irreversible processes occurring in a deformed solid as a thermomechanical macroscopic statistical system. The empirical characteristics of the indentation process are force, displacement, conditional indentation area, etc. The physical kinetic theory of hardness also uses additional characteristics. Conditional and physical activated volume (m^3); indentation energy density (J/m^3); specific generalized indentation power (J/m^3); molar energy density of the activated volume (J/mol); generalized indentation force growth rate (N/m); function and parameter of volume shaping ($1/m$), etc.

In [11], physical equations and universal physical molar kinetic strength parameters of a structural material are used to calculate the state of strength, durability, and limiting parameters of the state of the material. The physical molar parameters of the strength of a material are analytically related to the value of its physical hardness by kinetic indentation. Determining the universal physical kinetic parameters of a material has previously been a complex experimental and analytical task. At present, I have developed a new simplified method for determining the physical kinetic parameters of the strength and durability of structural materials [1]. It is based on a complex physical analysis of standard experimental diagrams of kinetic macro and nano material indentation. Methodologically, the physical theory of hardness of materials is divided into three types of analysis of kinetic (instrumental) indentation: macro, nano-micro and combined method. Next, the first stage is described - the physical method for analyzing macroindentation data. The main concepts, the activated volume, the density and power of the indentation energy, the function and number of physical hardness of kinetic indentation of a material, etc., are substantiated. The relationship between the values of the dimensionless number of empirical (standard) hardness and physical hardness is established. The physical reason for the size effect in empirical methods for determining hardness, etc. is shown. A theoretical basis for a correct physical method for comparing the macrohardness number of a material obtained by different tools, standards or methods is developed. The results obtained form the basis for further development of data analysis methods and the physical theory of nano-microkinetic indentation.

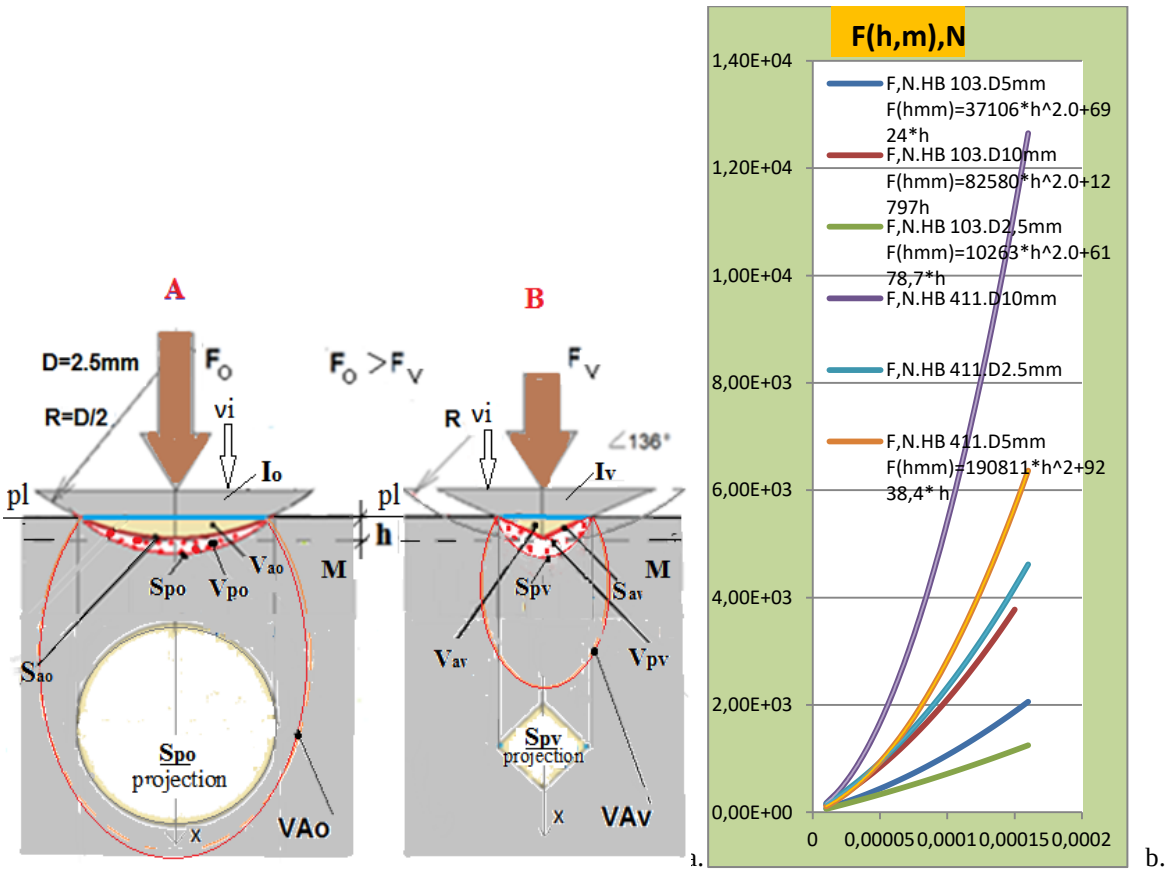
2. Physical criterion of material hardness.
Scheme of the macro indentation process.

To develop a physical model of the macro indentation process, we first construct a scheme of the mechanical process using the example of two macro surface methods, indentation with a Brinell sphere and a Vickers pyramid (sharp indenter). 1a,b. Designations Fig.1: M – material; Io - spherical Brinell indenter, Iv - Vickers pyramid; Subscript: o - sphere, v - pyramid. , - force on the indenter; VA - conditional activated volume, in which there are reversible (elastic stresses) and irreversible deformation processes; D is the diameter, R is the radius of the sphere. The volume boundary is shown conditionally as a red line. The upper boundary is the contact surface of the material sample. Activated volume Va(h) - the volume of the part of the indenter immersed in 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 occurred during indentation. h is the displacement of the indenter. vi, m/s. is the indenter speed. The volume Vp is limited by the surfaces Sa and Sp. It contains the material in a highly activated quasi-liquid state. - the entire outer surface created by the indenter. Sp - conditional external boundary Vp of the volume. Sac is the contact surface of the material and the indenter body. In general . Next, we assume. pl - plane, the basic surface of the material M. Projections of the contact surface: Spo, Spv. In this case, we take Va(h)= Vp(h).

Consider the scheme of the process of indentation by the Brinell sphere Fig. 1A, formulate the concept of a thermomechanical system of elements: indenter - material - testing mechanism (source of force). Let's denote the system as TMS (Thermomechanical System). For TMS, we will build a thermomechanical physical model of the kinetic process, justify the equation of state Vp of the activated material volume.

Physical model of thermomechanical system.

As a result of the movement of the indenter with a certain low speed, a quasi-equilibrium process of continuous energy exchange arises between the elements of the system. In front of the contact surface of the indenter body there is an activated (displaced) material volume Vp, Fig.2. he located between the contact surface Sa and the



a. b.

Fig.1a,b:.a. Scheme, longitudinal section, the process of forming material for macro indentation, on one scale: A - spherical Brinell indenter; B - Vickers pyramid; b. Kinetic macro indentation with a sphere, experimental diagrams F(h,D), diameter , standard hardness tests HB103, HB411, data [3];

imaginary vortex wave surface Sp - the boundary of states with different structural and energy parameters of the material. In the volume Vp as a result of kinetic indentation (hereinafter briefly CI), its own high parameters of the state of the material as an activated system are formed and stored. These options are marked with an asterisk *. Let us apply a special physical term from the monograph on thermodynamics [3].

The author argues that from the standpoint of statistical thermodynamics and physics, the force F creates stress and pressure in a material body, which can be represented as a flow of work in this volume of a thermodynamic system. The mechanical force F activates, at the elementary level of the structure of a solid body, the corpuscular-wave processes of the periodic movement of energy flows of quasiparticles between the structural units of a solid body (fluctuations in energy density, characteristic fluctuations) [1]. In a deformed solid, the energy flows of motion of quasiparticles form fields of stresses, pressures, and temperatures. This is a macroscopic process of a single corpuscular-wave statistical nature, it is characterized by the corresponding physical structural-energy molar state parameters [9,10]. In [1], a physical model of the work flow of stresses and pressure in a material medium was used to analyze the kinetic process of indentation. Figure 2 shows the physical energy model of the kinetic process of shape change and growth of the activated physical volume of a solid body using the example of macro indentation by a sphere. We assume that the process of formation of high parameters of the quasi-equilibrium activated state of the volume Vp occurs continuously during the movement of the indenter. The change in the parameters of the material structure, the transformation of the entropy of the state of the material, occurs in some small layer of the surface Sp (boundary region). The preparatory stage of relaxation, the formation of a stable transformation process, is supposed to be completed when h> h*. In Fig.2, the boundary region Sp is denoted by the symbols ø.This is the boundary of structural and energy transformations of the material during the formation of the volume Vp. All irreversible processes of translational-rotational transformations of the structure of the initial state of the material occur on the outer surface Sp, and latent energy is released [1]. The parameters of the initial state of the material T - temperature, P - pressure, $\hat{S}$ - entropy. We assume that the CI process generates on the surface Sp, new internal state parameters of the structural units , , , , and translates these parameters into the volume Vp . To describe the state parameters of the physical volume Vp, we use the methods of statistical thermodynamics [12]. To describe the process, we use the properties of the entropy of the structural state of a deformable solid [13], the physical theory of strength [10]. Suppose we are given an initial value of entropy (without load F), which uniquely characterizes the initial structural energy state of the material (SES). A similar approach was used in [13].

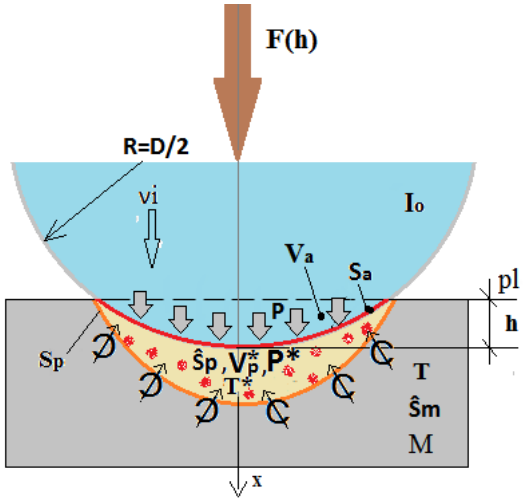


Fig.2 Physical model of the activated material volume as a thermomechanical system.

In the process of CI, in the activated volume Vp, material is accumulated with a new entropy value $\hat{S}_p^*$. The volume V_p^* accumulates additional energy from the decay (transformation) of the original crystal structure, the transformation of the energy of elastic stresses, and thermal energy. As a result, an activated volume V_p^* is created in which the transition from the solid phase to the quasi-liquid state of the material is completed. This volume accumulates the released part of the energy of the melting heat of the initial solid state of the material, from the destruction of part of the structural interactions of the solid phase [1]. During the CI process, the volume $V_p(h)$ continuously grows, while maintaining a constant pressure of the quasi-liquid $P_p^* = \sigma_{sh}^* = \text{const}$. In the external large volume VAo, the stress state changes, and the spherical compression tensor $\sigma_{sh}^*(h)$ of material compression increases. After the completion of the initial period of relaxation, h>h*, h* is the depth of the relaxation area, a quasi-equilibrium physico-mechanical uniform (laminar) process CI with a certain specific power was established in the volume $V_p(h)$. If h>h*, a uniform ɔ, homogeneous, stable process of transition of the source material to a new activated state has occurred in the layer ɔ. Thus, during the movement of a spherical indenter with a diameter D, with a certain small constant speed vi, a continuous, stable, laminar process of movement, shape change, structural transformations and volume $V_p(h)$ growth occurs with parameters P_p^*, $\hat{S}_p$, T_p^*. Studies have shown [1] that to create such ideal conditions, a spherical indenter must have a diameter D > Dmin. Where, Dmin is a sufficiently large indenter diameter required to maintain a monotonic laminar process of material structure transformations when the indenter is moved [1]. In this case, the value $V_p(h)$ of the activated volume can be considered as a generalized coordinate of the CI process. This is some monotonic increasing function of TMS.

We have formed a thermomechanical model of the laminar process of kinetic indentation by the TMS activated volume sphere. Consider its physical properties.

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

Consider $V_p(h)$ as a statistical thermodynamic system using the general provisions of thermodynamics, the physical theory of strength and fracture of solids. Let's assume that all preparatory physical structural-energetic processes of material transformation take place outside the volume $V_p(h)$ in the boundary area, it is marked with the symbol ɔ Fig.2. Initial material parameters: P, T, $\hat{S}$. On the outer boundary S_p of the volume $V_p(h)$, continuous structural and energy transformations of the material occur. A flow of energy moves through the physical boundary into the volume, 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 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 [12], the potential of the internal energy of the state of the system is equal to:

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

Where, U - is the potential of the internal energy of the thermodynamic system. Q - heat energy transferred to the system. A- is the work done by external forces on 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 is continuously growing, but the parameters $P_p^*, T_p^*, \widehat{S}_p^*$ are constant. As a result of changes in the structure of the external environment, energy enters the volume through the boundary S_p. This is the result of the translation of a new structural-energy state to an additional volume of material. There is a change in the entropy of the structure $\widehat{S}_p \to \widehat{S}_p^*$. The volume $V_p(h)$ of the system increases, while a quasi-equilibrium state is maintained in it. Thus, the amount of matter, the total energy U_p and volume, are continuously growing. The energy in the activated volume comes from the external region, so the sign of the potential work A in (3) should be changed to plus. Let us assume that the main part of the indentation energy spent in the irreversible process is dissipated in the volume . Thus, the activated volume represents the equivalent thermomechanical system (TMS) of the kinetic process. By definition, a thermodynamic system has a constant amount of matter. The amount of matter, the volume of our system is monotonously growing. Let's carry out a conditional transition to a thermodynamic system with a constant volume and amount of matter, and proceed to the analysis of the properties of a unit volume of our system.

Potential of the generalized specific power of indentation. Standard and physical value of macrohardness.

Let us assume that during laminar kinetic macroindentation there is a physical thermomechanical potential of the activated volume , 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 [14], the volume potential differential U_p (6) is the limit of the ratio of the energy increment and the activated volume increment:

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

Let us denote this volume differential of the energy increment:

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

Thus, we have found the change in the energy density per unit of the activated volume of this system during kinetic macroindentation. Since the depth h, the volume V, and the rate of the process vi are unambiguously interconnected quantities, the process time and the indentation volume are one-to-one. Therefore, we can use for (6a) $PHM(V_p)$ - the term generalized specific power of energy change per unit of activated volume. Briefly (6a), is the potential of the specific generalized power of macro indentation. In this case, volume is the independent variable, $V_p = V$. As a result, we have obtained (6a) a generalized isochoric - isobaric - isothermal thermodynamic potential of the generalized power 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 are constant values $\widehat{S}_p^* = const$, $T^* = const$, therefore $\partial U_p(T_p^* \widehat{S}_p^*) = 0$ Further, we do not write the asterisk index of the physical activated volume. Let us assume that all

work A is aimed at the processes of shape change and structural-energy transformations of the initial state of the material, during the formation of the activated volume $V_p(h) = V(h)$. In this case, the thermomechanical potential $A(V)$ of the activated volume is:

$$U_p = P_p V_p = A(V) \qquad (6.1)$$

According to ISO 14577 [10] , the work A(h) of the force F(h) spent on the shape change of the material volume when moving the indenter:

$$A(V) = A(h) = \int_0^{h_0} F(h)dh \quad (6.2), \qquad A' = \partial A / \partial h = F(h) . \quad (6.3),$$

$$U_p = \int_0^{h_0} F(h)dh . \qquad (6.4)$$

In what follows, we assume $V_p = V_a$; for simplicity of notation, we omit the subscript $V_p = V_a = V$. Using (4), (6), (6.1), we obtain the volumetric differential, let's call its potential the specific generalized power of macro indentation of the material:

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

According to the general field theory [14], the potential of the specific indentation power (7) is related to the gradient of the energy field density on the surface of the activated volume:-

$$PHM(V) = gradA = \frac{\partial A}{\partial V_x} + \frac{\partial A}{\partial V_y} + \frac{\partial A}{\partial V_z} = PHI_x(h) + 2PHI_z(h) \qquad (7.1)$$

Where, $gradA$ -is the gradient $A(V)$ on the surface S_a of the activated volume V(h) ,

$PHI_x(h) = \frac{\partial A}{\partial V_x}$, $PHI_y(h) = \frac{\partial A}{\partial V_y}$, $PHI_z(h) = \frac{\partial A}{\partial V_z}$, $PHI_y(h) = PHI_z(h)$, $PHI_{x,y,z}(h)$ - of the potential A gradient along the axes of Cartesian coordinates. Let's apply the physical definition to the specific power potential $PHM(V)$, (7.1) - energy field density gradient of the activated volume in the CI process on the boundary surface S_a . The potential can also be considered as the amount of energy flowing through the surface of the activated volume, in the process of changing the energy density of the structure of the material of the activated volume during shaping. Gradient (7.1) is the total specific generalized power of the energy density flux through the surface of the activated material volume V in the CI process.

Experimental properties of the potential of the specific generalized indentation power. Physical standard of macrohardness.

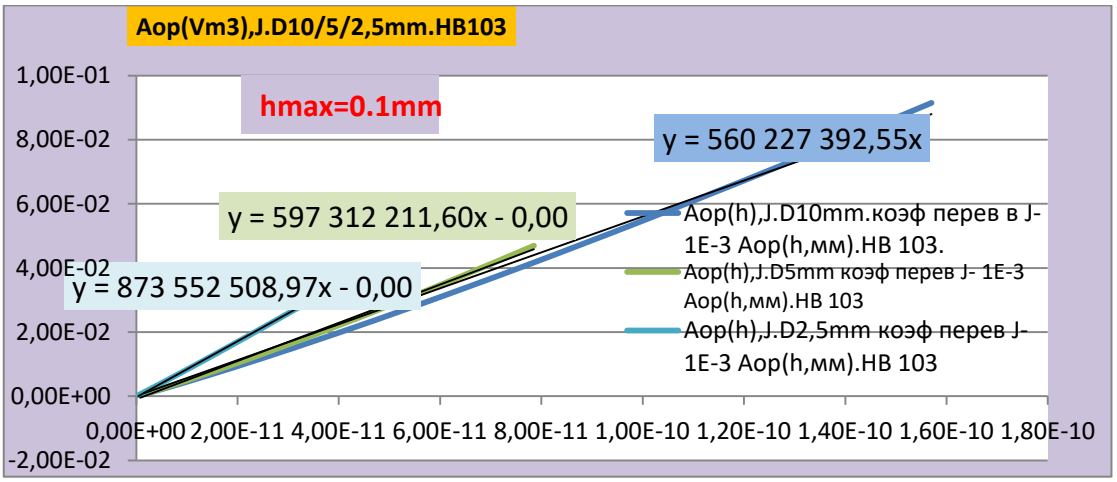
In [1], based on the analysis of the experimental diagrams F(h) [3], kinetic macroindentation by a sphere of different diameters of standard exemplary measures of different hardness, the functions of the physical thermomechanical potential were obtained $A(V, m^3)$. Figure 3 shows the functions $A(V, m^3)$, the integral of the function F(h). Standard measures of hardness, sphere diameter D10/5/2.5mm [2] were studied: a) Measures HB103/411, Measurement range h=0.1-033mm; Fig.3b Measure HB176. Range hmax=0.5-5.0mm. The linear trend equations for the approximation of each function are obtained (denoted by $y = A'_v x$). For this, Excel-2007 was used, linear trends $A(V, m^3)$ were built, a black line (a1, b2), a colored line (a2, b1).

Based on the analysis of the experimental results, example Fig.3, were analytically determined , formula (7) , the potential values of the specific generalized indentation power . A linear trend of the thermomechanical potential was built and the parameter of this trend was found, which is equal to the specific power potential:

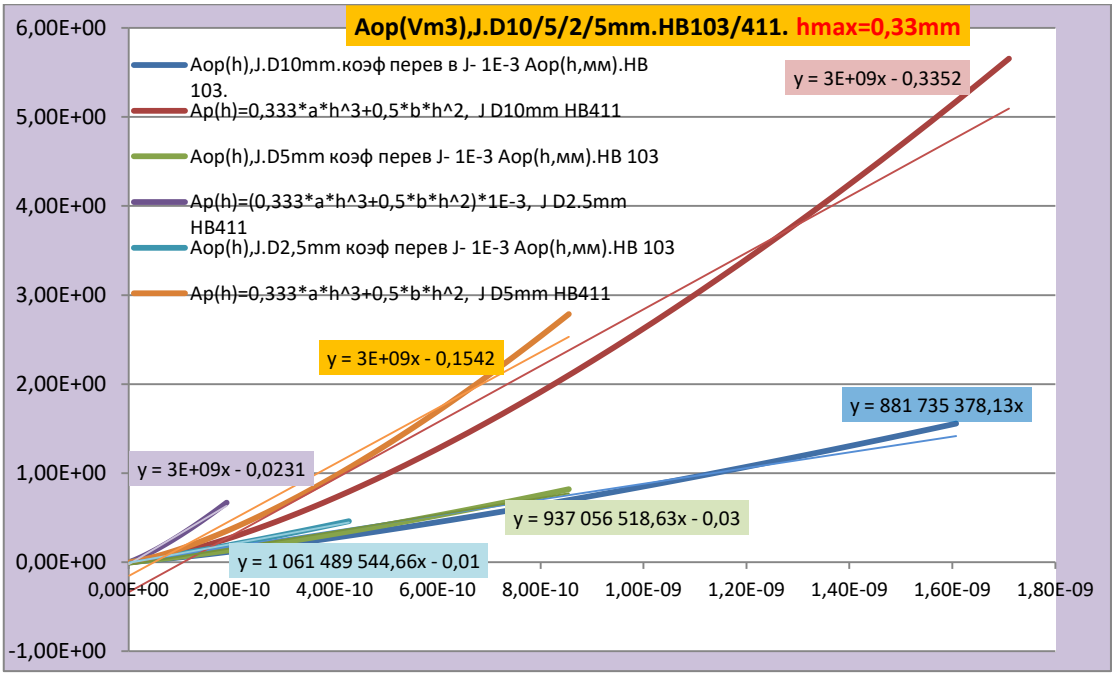
$$PHM(HB) = A'(V)_v = \frac{\Delta A}{\Delta V} \approx \frac{dA}{dV} = const , \ J/m^3 \qquad (7.2)$$

Where, $A'(V)_v$ is the parameter of the linear trend of the function , according to (7) this is the potential of the specific generalized indentation power, then we will apply the term to it: the physical macrohardness of the laminar indentation of the material. This is an integral energy characteristic of the change in the structural and physical

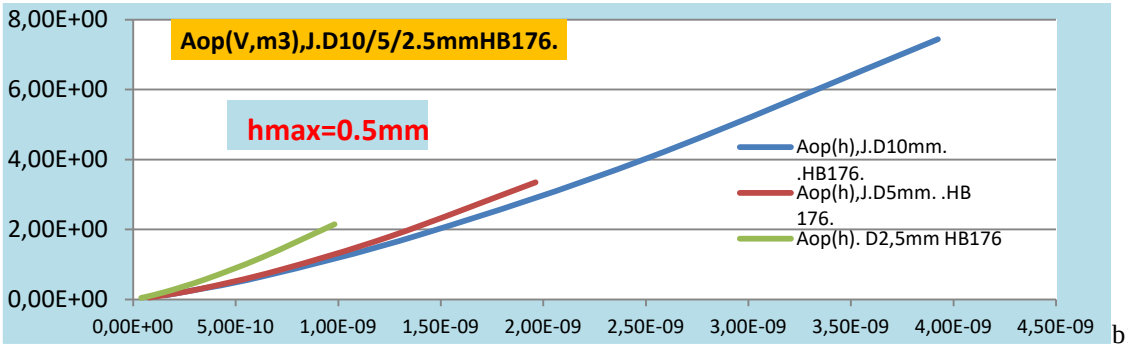
properties of the material in the CI process. The results of calculating the physical macrohardness or indentation potential $PHM(HB)$ of different hardness measures are in Table 1.



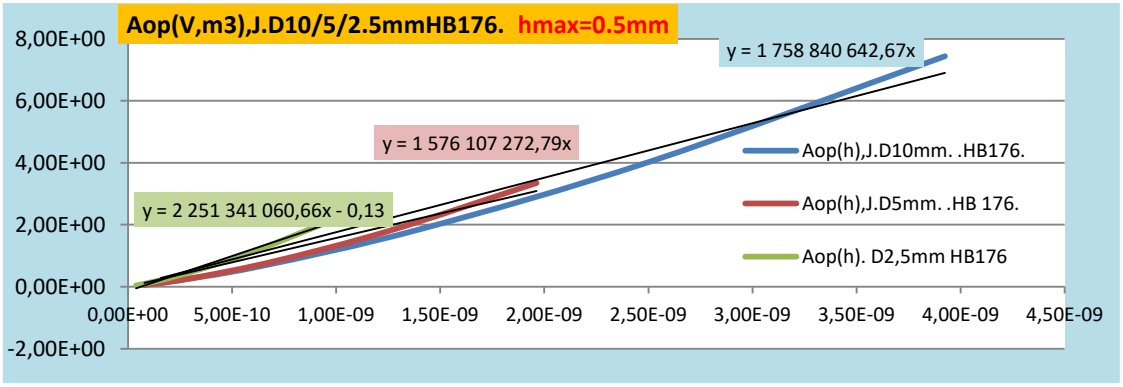
a1.



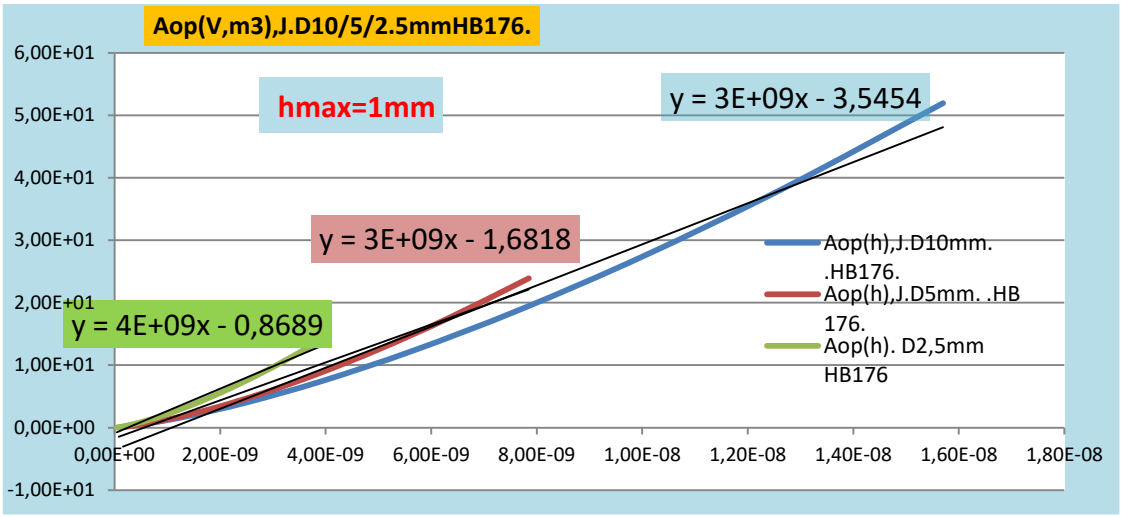
a2.



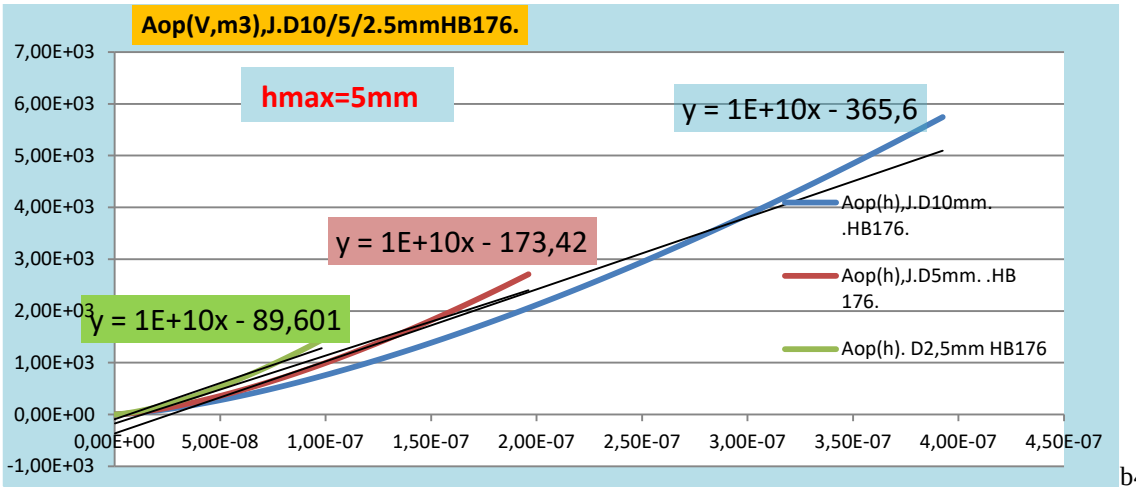
b1.



b2.



b3.



b4.

Fig.3a,b. Approximation of the potential $A(V,m^3),J$ kinetic laminar macro indentation. Indenter sphere D10/5/2,5mm. The equation and linear trend $A'(V)_v$ parameter for each function is shown. Used Excel 2007: a) 1.2 standard hardness test blocks HB103/411, range h max=0.1 and 0.33mm; b)1,2,3,4 HB 176. range h max= 0.5/1.0/5.0 mm. Experimental diagrams F(h) from [3].

From (7) and the results of the analysis of experimental data, it follows that the thermomechanical potential over a large interval h is a linear function:

$$A(V) = PHM(HB) \cdot V_a = A'(V)_v \cdot V_a \ , J \qquad (7.3)$$

Physical hardness, according to the results of indentation of a standard measure with a sphere Table 1.

standard measure of hardness	Mean physical hardness of indentation $PHM(HB)$, $J/m3$	Physical hardness values for indentation hardness test blocks HB103/176/411, diameter 10/5/2.5 (D, mm.) $PHM(HB) = A'(V)_v$, $J/m3$		
HB411	$3.2 \cdot 10^9$	$3{,}1 \cdot 10^9$, (D2,5	$3{,}1 \cdot 10^9$, (D2,5)	$3{,}4 \cdot 10^9$, (D10)
HB176	$1.85 \cdot 10^9$	$2{,}23 \cdot 10^9$, (D2	$1{,}58 \cdot 10^9$, (D5)	$1.76 \cdot 10^9$, (D10)
HB103	$0.94 \cdot 10^9$	$1.0 \cdot 10^9$, (D2,5	$0.94 \cdot 10^9$, (D5)	$0.89 \cdot 10^9$, (D10)

Conclusion.

With a laminar macro CI with a Brinell sphere, the process of material shaping is characterized by a linear function. The volume potential is equal to the product of the physical macrohardness potential of the material (7.2) and the activated volume $\cdot V_a$. Another formulation of dependence (7.3): the volume potential of the activated volume of macrolaminar indentation $A(V)$, is equal to the product of the specific generalized indentation power potential (7) $PHM(HB)$ - and the activated volume V_a .

In general, the volume potential $A(V)$ is a non-linear function, the properties of which depend on the homogeneity and anisotropy of the material, the shape of the indenter, the magnitude of the force and the displacement depth h during the CI process. We considered the CI process for a homogeneous, isotropic, stable material, these properties have standard hardness tests that we used in the work.

$PHM(HB) = A'(V)_v$ - potential of physical macrohardness of laminar indentation of material by a spherical indenter (7.2). A stable, objective experimental physical characteristic of the macrohardness of a solid body is obtained, which does not depend on the size of the indenter and can be a universal physical standard for measuring macrohardness. Our studies were carried out for a sphere-shaped indenter with different diameters, constant movement speed, homogeneous, isotropic, and stable material. In the depth interval $0.1 < h < 0.33mm$ of indentation by the sphere, a stable value of the physical hardness potential was obtained $PHM(HB)$. The physical hardness $PHM(HB)$ obtained for a standard measure is equal to the Brinell $PHM(HB_i) = HB_i$ hardness number of the given measure but in the dimension $J/m3$. In Table 1, for HB103, HB176, this case is highlighted in green. Equality of values takes place if the depth of empirical indentation of the standard measure (it is not controlled in empirical methods) falls within the interval of the potential $PHM(HB)$ measurement depth. The coincidence of physical and empirical hardness takes place if the condition of physical similarity of processes is satisfied, the depth of indentation when measuring the hardness number with a sphere falls within the measurement interval for the physical method. The discrepancy between the values of physical and empirical hardness takes place, this is the result of a statistical spread of material properties and the influence of random factors in the measurement method.

The method for calculating the physical hardness of a material based on the analytical processing of the kinetic diagram F(h) has a number of advantages. There is no size effect. The influence of the measurement range and interval on the physical hardness number is insignificant, it can be eliminated by using a special indenter shape (for example, a truncated Calvert-Johnson cone). Physical methods for analyzing kinetic indentation data make it possible to analytically substantiate the harmful effect of various factors in the standard test procedure on the value of physical hardness. When calculating the potential of the material, one can take into account the influence of the shape of the indenter, the influence of the integration interval. The physical method for determining the hardness of a material from the force diagram of kinetic indentation reduces the requirements for accuracy and technology of the measuring process, etc. Discussion of the advantages and properties of the new method is the subject of a separate article.

Physical hardness considers the total energy of the process, without separating plastic and elastic deformations.

The results of our studies and conclusions coincide with the ideas of the authors of [7], in which it was proposed to use the specific indentation energy as an indicator of material hardness. In [15], in order to eliminate the size effect, it is proposed to fix the imprint size (depth) during hardness measurements; these proposals confirm the results of our theoretical studies. The physical process of CI in the nano-micro-macro range with a sharp tool like a pyramid, cone, nano-sphere, etc. is characterized by special parameters, its own indentation equation [1]. Theoretical methods for determining physical hardness and other parameters for the nano-micro range and taking into account the influence of shape features indenter were studied in [1].

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Part 2

Physical properties of the function and number of empirical macrohardness of the material. Universal physical unit of measurement of macro hardness.

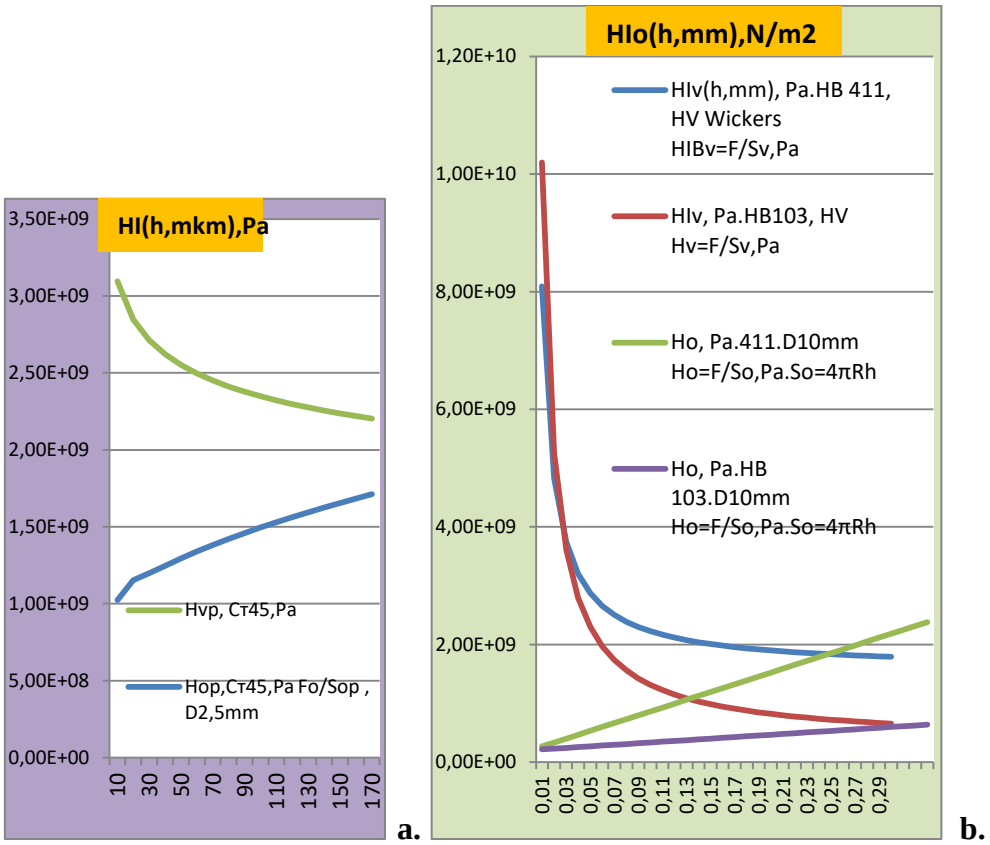
Function and number of empirical macrohardness, physical properties. Method for comparing the values of physical and empirical macrohardness.

Let us consider, using the example of indentation by a sphere, the properties of the function HI(h) and the number of empirical macrohardness of the material using physical analysis. Let us discuss the reason for the size effect. The results are presented in detail in [4]. Figure 1b shows a characteristic view of the **CI** diagram F(h), a spherical indenter of different diameters, standard HB103 and HB411 hardness blocks. On Fig. 4a,b diagrams of empirical hardness obtained by the formula HI(h)=F(h)/S(h). Here S(h) is the conditional area of contact and distribution of the action of the force F on the material. HI(h) - empirical hardness according to Brinell, has a conditional dimension N/m^2 , this is a conditional pressure or conditional compressive stress on the contact surface. Usually, the area S(h) is determined by the formula

proposed in the hardness measurement procedure. In hardness calculations, conditional geometric characteristics of the surface created in the process of pressing the indenter body into the material are used. The formulas determine the area of the conditional surface of a dent or imprint (a dent after the removal of the force F), the projection of the surface, etc. All formulas for calculating the area S are approximate, conditional, empirical, do not have a correct physical connection with internal irreversible processes of material structure transformations. Models of plastic deformations of a material belong to the theory of mechanics of a deformed solid body, they do not contain statistical physics. The task of physical theory is to establish the relationship between changes in the structural-energy parameters of the material and empirical parameters (F,S,V,h) of kinetic indentation. Using the example of the Brinell method, we will consider the relationship between the number and function of empirical and physical hardness.

In (7.1), the gradient of the energy field density of the thermomechanical indentation potential A on the surface of the activated volume is determined. We also indicated that the gradient of the indentation potential is the **physical macrohardness of the laminar indentation of the material**. In Cartesian coordinates, the total increment of the activated volume is the sum of partial differentials, let's call them components of the density potential gradient, according to (7.1):

$$\mathrm{gradA} = \frac{\partial A}{\partial V_x} + \frac{\partial A}{\partial V_y} + \frac{\partial A}{\partial V_z} = \mathrm{PHI}_x(h) + 2\mathrm{PHI}_z(h) \qquad (9)$$



Rice. 4. Kinetic macro indentation with a sphere and a pyramid. Diagrams HI (h) of empirical macro-surface hardness: a) Experimental. Upper curved Vickers pyramid, lower Brinell sphere D2.5mm. Steel 45, data [11]; b) Extended chart range HI=F/So, empirical hardness, (9.6) HB103/411, D10mm, pyramid Wickers, built analytically, initial data [2].

The shape of the indenter (sphere, pyramid, etc.) affects the value of each component. The magnitude of the increment of the component depends on the coordinate axis and the shape of the surface of the activated volume, respectively, and the shape of the indenter. According to the gradient theory [9], each component characterizes the increment of potential energy density A on the surface S of the activated volume. Consequently, each component of the gradient (7.1) characterizes the change in the energy density in the direction of the chosen axis. In the direction of each axis, we have a certain specific generalized power. The component of the physical hardness potential depends on the selected direction, depth, hardness of the material and the shape of the indenter. Let us denote $PHI_x(h, HB)$ - the main component of the gradient of the generalized power of macroindentation of the material in the direction h. Let us study the main component of the potential gradient in the direction of indenter movement, the X axis, Fig. 1a, h = x. Volume partial differential in h (X-axis):

$$PHI_x(h, HB) = \frac{\partial A_x}{\partial Vx} = \frac{\partial A}{V'_p(h)\partial h} = \frac{A'(h)\partial h}{V'(h)\partial h} = \frac{A'(h)}{V'(h)} = \frac{F(h)}{V'_o(h)}, N/m^2 \qquad (9.1)$$

Где, из (6.3) $A' = \partial A / \partial h = F(h)$, $\partial Vx / \partial h = V'(h)$. (9.2)

For laminar macro indentation $A_x = \mu A$, μ is the parameter of the influence of the shape and direction of the axis on the function $S_{x,y,z}(X, Y, Z)$ of the indenter surface area component , for a sphere, h>>0, we will approximately accept $\mu \approx 1$, we will obtain $A_x \cong A$.

From the approximation of the function $F(h)$ by a polynomial, for the sphere and pyramid [2] we have:

$$F(h) = ah^m + bh^{m-1} + c \qquad (9.3)$$

Where, a, b, c, m are approximation constants. In [4] for macro CI with a Brinell ball and a Vickers pyramid, for standard hardness tests, it was established: m = 2, values, $a = a_0$ $b = b_0$ in work [4], $c = 0$. From (9.1),(9.2), (9.3) we obtain in general form:

$$PHI_x(h, HB) = \frac{\partial A_x}{\partial Vx} = \frac{F(h)}{V'_o(h)} = \frac{F(h)}{2\pi Rh} = \frac{F(h)}{S_{ax}} = \frac{a_o h^2 + b_o h}{2\pi Rh} = \frac{a_o h}{2\pi R} + \frac{b_o}{2\pi R}, N/m^2, \quad (9.4)$$

Where, $V'_o = \partial V_o / \partial h = 2\pi Rh = S_{ax}$.

Substituting the partial derivative $V'_o = S_{ax}$ in (9.1) we get:

$$PHI_x(h, HB) = \frac{\partial A}{\partial Vx} = \frac{\partial A}{V'_p(h)\partial h} = \frac{\partial A}{S_{ax}\partial h}, N/m^2 \qquad (9.5)$$

From (9.5) it is obvious that the main component of physical hardness or the component of the generalized indentation power function $PHI_x(h, HB)$ is the specific amount of the energy flux gradient, therefore, the value is determined per unit area $S_a(h)$. From (9.5) it is obvious that the main component of the indentation gradient depends on the work done and the area of the contact surface (respectively, on the depth). Thus, there are two options for representing the power gradient component or the macro physical hardness component CI (9.1) and (9.4). Let's consider them in detail:

First option. Dimension of volume differential of physical hardness of indentation J/m^3, (7). For the sphere formulas, (9.1), (9.4), as a result of transformations, the physical dimension J/m^3 degenerates (reduces), we obtain the dimension of empirical hardness N/m^2 . Therefore, in formulas (9.4), (9.5) the dimension of conditional stresses. Formulas (9.1), (9.4) are converted into the empirical hardness formula $HI(h)$ (9.6):

$$PHI_X(h,HB) = \frac{\partial A_x}{\partial Vx} = \frac{\partial A}{S_a \partial h} = \frac{F(h)}{2\pi Rh} = \frac{F(h)}{S_{ao}(h)} = HI(h), N/m^2, \text{ Где, } S_a(h) = \delta\pi Rh$$

The final empirical hardness is the main component of the gradient of the generalized macroindentation volumetric power , divided by the area :

$$PHI_X(h,HB) = HI(h), N/m^2, \quad (9.6)$$

Thus, empirical hardness is twice the specific indicator. **The empirical hardness** depends on the energy density A dissipated in the volume V_0 and the energy density gradient on the surface of the activated volume, moved in the direction of the **h-X** axis and changed in shape. This is the main component of the gradient (9.5) of physical hardness, it is equal to the empirical hardness (9.6). Characterizes the change in the energy density of indentation, when moving from the activated volume to the outer region of the indented material, in the direction of the axis of motion.

Second option. Expanded formula of the physical hardness component CI sphere. Shows the relationship with the main approximation parameters a_0, b_0 in the function F(h), (9.3):

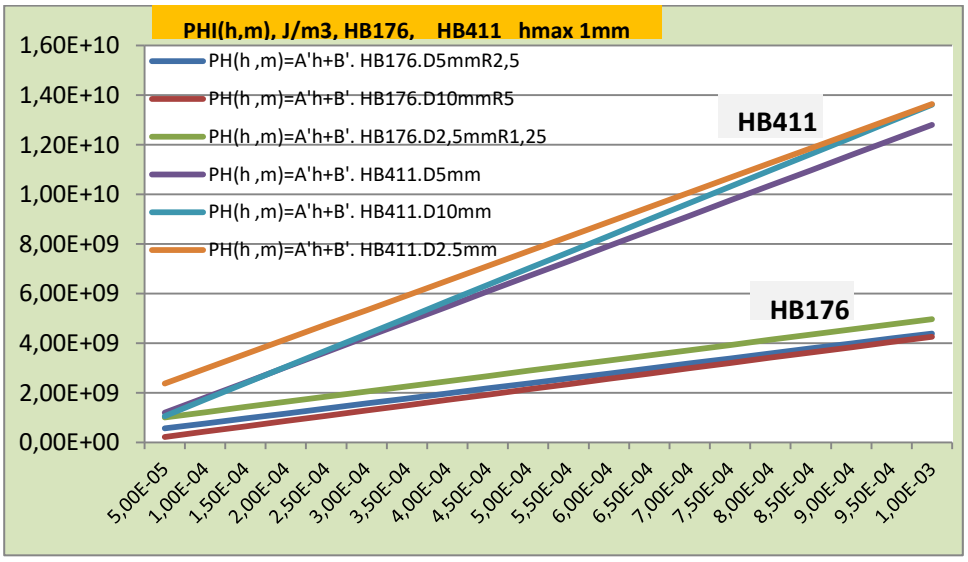
$$PHI_X(h,HB) = \frac{\partial A(h)}{\partial V_a(h)} = \frac{a_o h}{2\pi R} + \frac{b_o}{2\pi R}, N/m^2 \quad (9.7)$$

Summarize. The partial differential $PHI_X(h,HB)$, (9.5), (9.6), is also a function of the empirical hardness of the material in the Brinell method. This function contains the main component of the gradient (7.1), (9) . Empirical hardness is a specific characteristic of the stress work flow. As the depth h increases, the value of the empirical hardness, the main component of the gradient for the sphere, continuously grows linearly. In Fig.5a, an example $PHI(h,HB)$ for a material of different hardness. Figure 5b shows together $HI(h)$ the empirical hardness function and the gradient component function $gradA_X = PHI(h,HB)$, HB411 hardness block, sphere D5mm. The functions of physical and empirical hardness of one material (standard measure) coincide. The slope of the linear function $PHI(h,HB)$ and $HI(h)$ depends on the hardness.

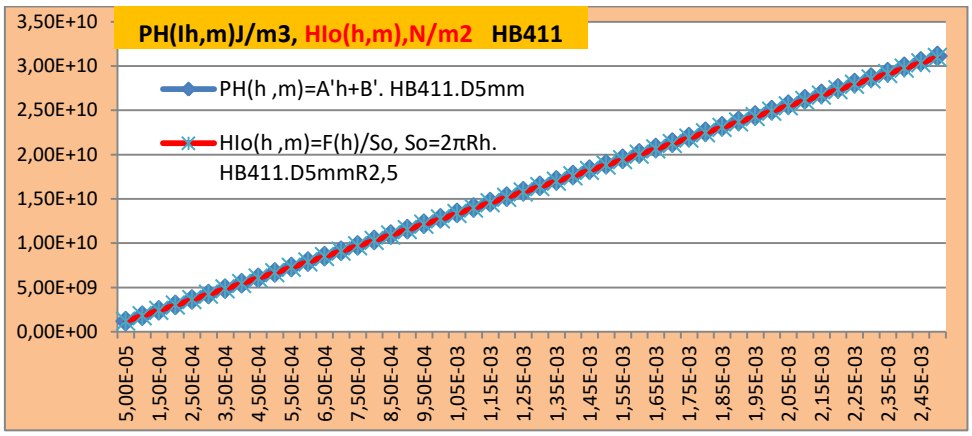
Similarity criterion for measurements of physical and empirical macrohardness. The standard of macrohardness of indentation by a sphere.

Figure 5a shows the characteristic functions $PHI(h,HB)$ for different HB176/411 hardness measures. For one measure of hardness, regardless of the diameter, the graphs of the functions almost coincided. For one measure HB_i, the function of empirical hardness or the component of the physical hardness gradient $PHI(h,HB)$ is invariant to the diameter of the sphere, the lines for three different diameters D almost coincided. Figure 5b shows together the functions $PHI(h,HB_i)$ and the empirical hardness HB_i for the measure HB411, they are the same. The value of the function or the hardness number, we calculate for a

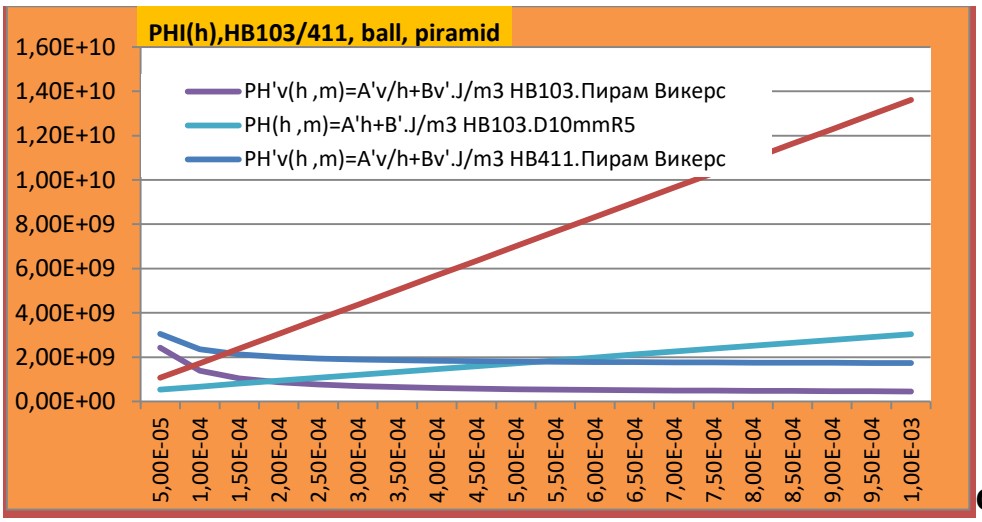
certain depth h. The value, the hardness number, depends on the chosen coordinate – the indentation depth h. It follows from the analysis that in order to unambiguously and correctly determine the number of empirical hardness of a material, it is necessary to ensure the same physical conditions or similarity of testing processes for materials of different hardness, take into account the shape of the tool and the depth h. In this case, we have macro indentation by a sphere, the similarity of physical conditions is provided at one given depth h_{st} , regardless of the diameter of the sphere. For a sphere, the standard for measuring hardness is - a constant indentation depth. At the same time, this is the first condition for the similarity of the physical process of macroindentation. Figure 5D shows the principle of determining the reference hardness values of different materials with a macro indenter. Provided that $h_{st} = h$ the physical similarity of processes is observed, for different materials, in this case, standard measures of hardness. Table 2 shows the results of calculating the physical hardness number for a conditional standard constant value of the indentation depth $h_{st} = 0.25mm$.



a)



b)



C)

Rice. 5 Function of physical and empirical macrohardness **CI**: a) physical hardness $PHI.(h, HB, D_n)$, standard measure of hardness HB176, HB411, diameter D10/5/2.5 mm, according to [2].; b) $HI(h)$ and $PHI(h)$ are shown together, HB411, D5/2.5 mm; c) Vickers sphere and pyramid diagrams.

In **Fig.5c**, the hardness functions $PHI(h)$, measure HB103, indenter sphere and Vickers pyramid. For a pyramid (also for a cone), the function has the form of a hyperbola; with a change in hardness, the graph shifts; the features of the **CI** process with a sharp indenter are considered in [4]. From the properties of the function and the definition of physical hardness, we see that the similarity is fulfilled if the indenter during the movement of CI generates the same specific value of the surface area $\Delta S_a / \Delta V_a, 1/m$, for different materials and different shapes of the indenter.

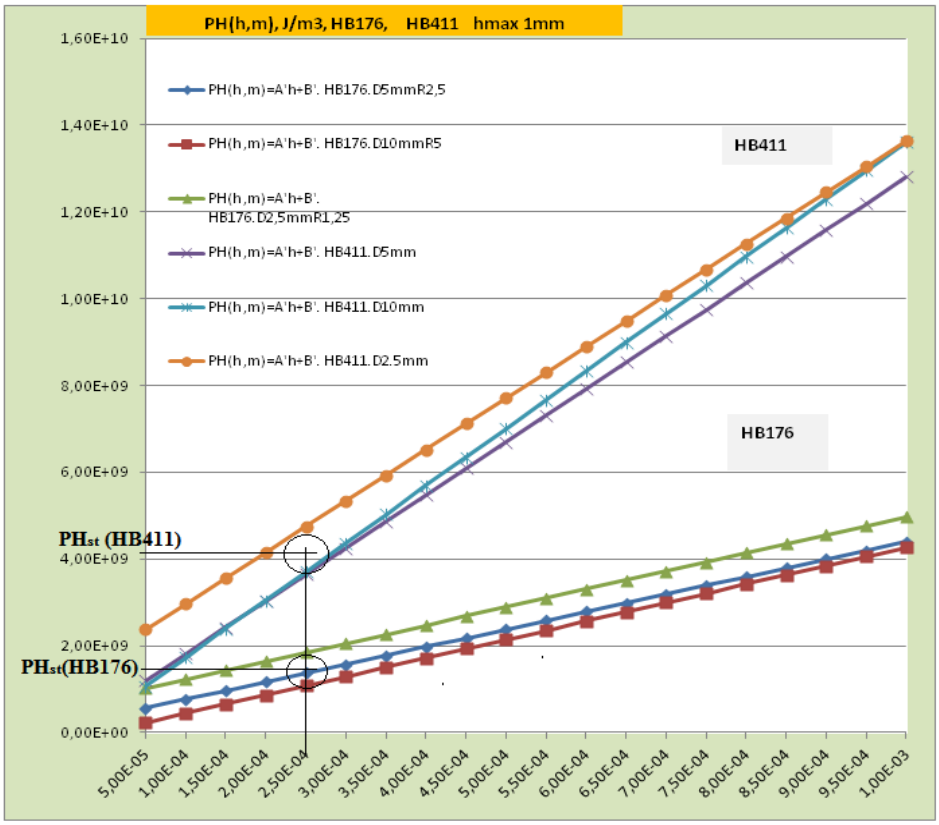


Fig.5D Determination of the value of the standard of physical - empirical hardness, using the experimental charts of physical hardness PHI (h), for standard measures HB176, HB 411, indenters sphere D = 10.0 / 5.0 / 2.5mm:. The value of the standard of physical hardness PH_{st} is approximately equal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

The calculation and comparison of the hardness number of different materials, indenters, should be performed under physical and mechanical similarity of conditions - the same increase in surface area per unit of activated (displaced) volume V_a . Such conditions for measuring the hardness of a material were first created by Calvert-Johnson (1859) [2]. In [4], in order to check the compliance with the condition of similarity of the macro process **CI** , a generalized physical and mechanical characteristic (10) of the material shape **change function is proposed:**

$$X_{SV}(h) = \frac{S_a(h)}{V_a(h)} \qquad (10)$$

$X_{SV}(h)$ - specific area of the created (generated) surface per unit volume of material activated in the CI process. The value of the function, in general, depends on the shape of the indenter and displacement h.

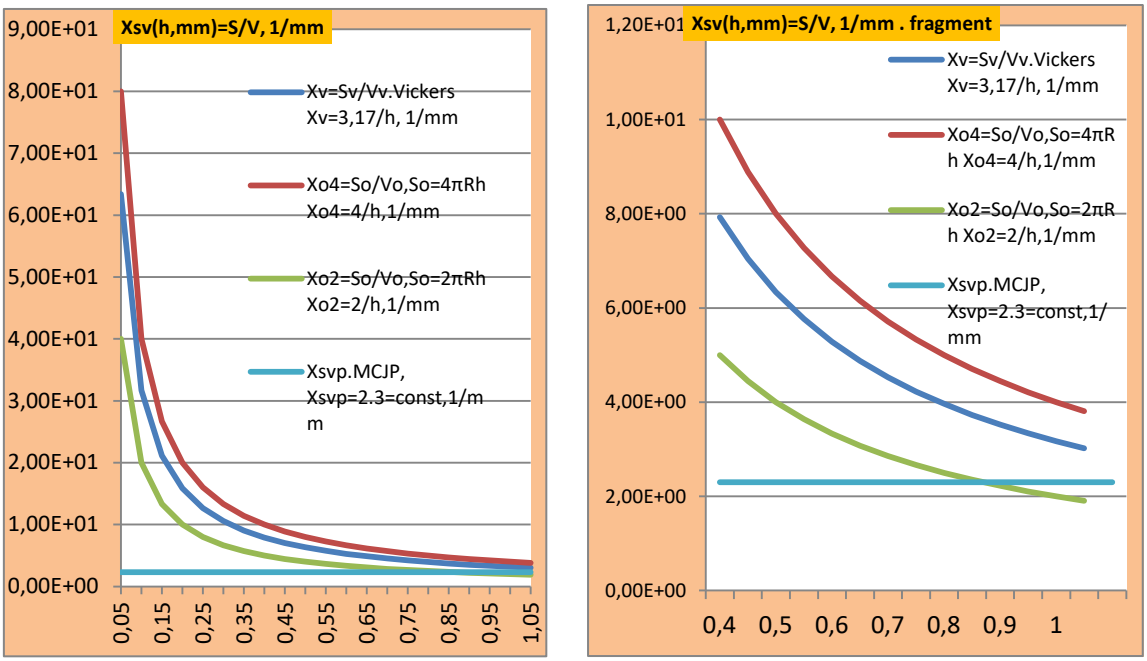


Fig. 6. Volume shaping function $X_{SV}(h)$ for pyramid, sphere, cone MCJ. For sphere $S_{ao}(h) = \delta\pi Rh$, δ=2, δ=4. Truncated cone indenter, MCJ method, $X_{SVP}MCJ \approx 2{,}3.1/mm = const$

For a sphere, function (10) has a special property (10.1), it does not depend on R, but depends on the indentation depth h and the parameter in the contact surface formula (determined by an empirical method):

$$X_{SVo}(h) = \frac{S_{ao}(h)}{V_{ao}(h)} = \frac{\delta\pi Rh}{\pi Rh^2} = \frac{\delta}{h}, \quad \delta = 2 \div 4 \qquad (10.1)$$

For the pyramid:: $X_{SVv}(h) = \frac{\lambda}{h}$, (10.2)

Where, λ is a parameter that takes into account the influence of the shape of the pyramid

$Sa = \lambda h^2$. For the Vickers pyramid $\lambda = 3.17$. In Fig.6, the functions $X_{SV}(h)$ for the indenter are sphere, pyramid and truncated cone.

The value depends $X_{SV}(h)$ on the shape of the indenter and the depth h. The specific indicator is affected by the formula for calculating the contact surface $S_a(h)$, an example is shown for a sphere, two formulas $S_o(h)$. Similarity condition when measuring macrohardness:

$X_{SV}(h) = \text{const}$, (10.3).

In the first physically correct method of hardness measurement, developed in 1859 [12] by Calvert-Johnson (denoted as MCJ), a truncated cone indenter was used, this shape has the property $X_{SV}MCJ \approx \text{const}$, Fig.6. More on the method in detail.

When measuring the hardness number in a laminar CI process, the specific surface area of the material must be the same. In this case, the similarity of the process of measuring the hardness number and the physically correct scale are preserved. In Fig.6b of the diagram $X_{SV}(h)$, we see that the similarity condition (10.3) is approximately satisfied for the sphere and the pyramid, if $h > 1.0mm$. From this depth $X_{SV}(h) \approx \text{const}$, the physical hardness depends little on the depth h, the influence of the initial nonlinear section decreases, and conditions are created for correct measurements of the hardness number CI.

The values of the empirical standard hardness HB and the physical hardness potential (7.3) $PHM(HB)$ coincide (close) if the potential is determined in the interval that contains the value h, at which the hardness HB is determined according to the standard Table.1,2. At the same time, the values of the shape change parameter are $X_{SV}(h)$ close.

From the analysis of macrokinetic indentation functions Fig.5,6,7 it follows that a physically correct comparison of empirical hardness values in standard tests is possible if an indenter of the same shape is used (a sphere can have different D). When determining the hardness number, a constant depth is needed h_{st}, Figure 5D.

For a different indenter shape, a physically correct comparison of the macrohardness number is possible only with the same value of the parameter $X_{SV}(h)$, the same depth does not provide similarity. Physical similarity of measurements of empirical hardness of different methods, tools and materials is performed under the condition (10.3).

Table 2 gives the values \u200b\u200bof the standard reference physical differential hardness, defined by the formula (9.2, 9.4), for $h_{st} = 0.25mm$, $D_i = 10/5/2.5mm$, three standard hardness measures HB103/176/411 The physical standard of standard depth $h_{st} = 0.25mm$ was adopted previously for comparative analysis. At the point h_{st}, the value PH_{st} and the empirical number of the standard measure HBW of Brinell hardness are approximately equal. The dimensions of physical and empirical hardness are formally reduced to the same value.

Physical hardness of standard measures for different sphere diameters. Table 2.

Mechanical measure of hardness HBW	PH_{st} **average physical hardness** $J/m3$	**Reference physical hardness value (9.4)** PH_{st} $J/m3$, **, different measure of hardness HB, diameter 10/5/2.5 (D,mm).** $h_{st} = 0.25mm$		
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)

To fulfill the similarity conditions in standard methods, the hardness number should be determined for the same tool shape and a constant value of the indentation depth. 7b. If a different tool shape is used, then it is necessary to perform an appropriate corrective calculation, satisfy condition (10.3) [4]. In this case, it is analytically possible to create a similarity of measurements with different tools, to perform a transition to another hardness scale, or to convert hardness number values using a universal physical unit of hardness. About the effect of different indenter shape, range on the hardness number, see [4] for more details. Due to the shape of the truncated cone indenter in MCJ, the similarity and condition (10.3) are met mechanically.

Physical properties of the hardness measurement process by the Calvert-Johnson method.

The paper [4] considers a physically correct method for measuring hardness, which was developed by Calvert-Johnson (1859) [12]. The authors of MCJ used a truncated cone indenter, initial contact diameter d=1.25mm, $X_{SVP}MCJ \approx 2{,}3 = const$. This shape of the indenter ensures the fulfillment of condition (10.3), $X_{SV}(h) \approx const$, see diagram Fig.7a,b. This is a property of the truncated cone shape, not the material. Thus, when measured, the depth h in MCJ had almost no effect on the hardness number. Form change, surface formation, occurs approximately at $X_{SV}(h) \approx const$. The MCJ experiment ends at point h_{st} , volume $V_a(h_{st})$. The MCJ did not measure the area and depth of indentation. We measured the required weight of the weights for the process of slow indentation, to a given depth h_{st}. The test time is always 30 minutes. The speed of movement of the indenter is approximately constant, conditions close to stationary creep are created. The value of the total weight of the weights, up to a constant factor, is equal to the work of indentation. The displaced volume and the contact surface area of the dent are the same for different materials. The total weight of weights for material of different hardness is different. But the root, physical indicator is the specific work of the weight of the weights. The weight is proportional to the specific work ($J/m3$) of the indenter. Thus, the MCJ indirectly measures the indentation energy density ($\Delta A/\Delta V$) of the material. The first MCJ hardness scale was built on the basis of a comparison of the physical energy criterion of hardness. Different material - different energy density (generalized specific

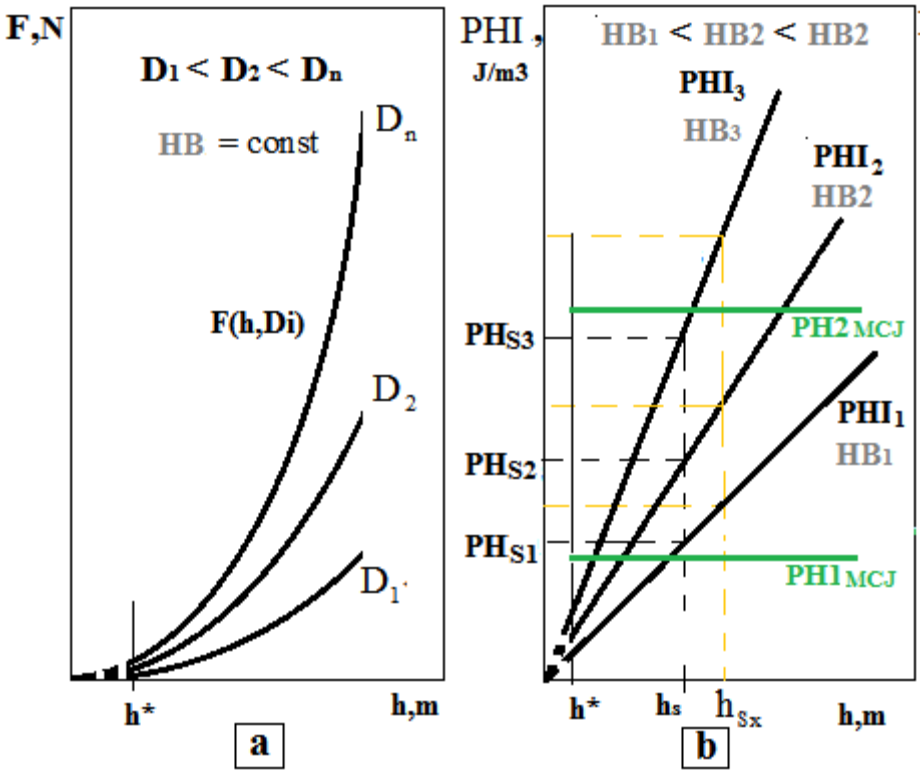


Fig.7. J Generalized diagrams of ideal laminar macro process CI by Brinell ball and cone MCJ: a) Function $F_n(h,D_n)$ diameter $D_1 < D_2 < D_n$, measure $HB_i = const$; b) function $PHI_i(h,HB_i)$ and standard PH_{Si} of physical hardness of each measure of hardness HB_i, D - arbitrary diameter, D> Dmin, $h < D$. Physical diagrams of CI hardness $PH1_{MCJ}$, $PH2_{MCJ}$ Calvert and Johnson method, conditional soft and hard material, respectively, $X_{SV}(h) = const$.

power) of forming, different hardness. There was no size effect in MCJ, the original scale was created in units of weights, a unified scale for the hardness of materials from lead to cast iron [12]. After that, the authors converted the energy (weight) hardness scale into a dimensionless one. There was no theoretical physical definition of hardness by the Calvert-Johnson method. An analysis of this method [4] showed that the basic physical principle of macro-instrumented indentation was intuitively created in it. The method has been used for over forty years. In subsequent methods of measuring hardness, the MCJ scale was supported empirically, artificially. During this period of time, according to our assumption, an erroneous opinion was formed about the absence of influence on the hardness number by the ratio of the dimensions of the activated volume and the area of the contact surface, etc. The principle of similarity was lost in the new methods. The methods of data processing of a mechanical act, the shape of the tool, the algorithms for measuring the hardness number (different geometry parameters, forces, etc.) have changed. As a result, an incorrect empirical approach has been established, in which the original hardness scale is “artificially” maintained.The hardness (number) or the potential of the physical specific power of forming in MCJ does not depend on the depth of the tool movement h. 7b, green lines. The shape of the indenter and the measurement rules in MCJ allowed the authors to form a basic correct physical scale of hardness. It became the basis for subsequent research, etc. The very physical principle of MCJ was subsequently unreasonably distorted.

The discussion of the results.

As a result of an analytical study of the properties of the CI diagrams of various standard hardness measures, a stable characteristic of a solid material was found - physical hardness, Table 1. The main component of the gradient of physical hardness , under the condition of physical similarity of measurements, is equal to the value of the empirical hardness of this material on the Brinell scale. At the same time, the stable and fundamental nature of the relationship between the functions of physical hardness CI and empirical hardness is shown analytically.

From the analysis of the results of calculating the potential of physical hardness, it was found that this is a constant value, an objective physical characteristic for a given material. In a wide range of h values, the potential is numerically equal to the single value of the component of the physical hardness potential , at the same time it is numerically equal to the empirical hardness of HB of a given material (standard measure) under conditions of physical similarity. The value of the potential , does not depend on the trajectory of the process F(h). The property has been experimentally confirmed for different material hardness, different sphere sizes. These results confirmed the assumption that under macro CI by ISO 14577-1:2002 standard methods, there is a state function, the thermomechanical potential of the activated material volume (3), (6.1). An objective characteristic of the physical-mechanical property of the hardness of the material for laminar CI is found.

In the works of researchers [13,14,15], the physical criterion of the specific energy of kinetic indentation was also used to assess the hardness of the material. Experimental results have been obtained in which there is practically no size effect at the same imprint size [15]. The authors of [13] suggested using the specific energy index CI to determine the hardness of the material. In these studies, a special case of CI is analyzed, there is no theoretical and physical generalization of the properties of this process, there is no physical analysis of the empirical method of measuring hardness. At the same time, these works experimentally confirm our theoretical assumptions and conclusions about the physical cause of the size effect.

Size effect in the measurement of 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 of specific power $PHI_i(h, HB_i)$, 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 PHI_i of material formally increased. The scale with the new hardness scale (depth h_{sx}) 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 is no criterion for 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 of materials 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. The truncated cone indenter MCJ provided the same physical conditions in each act of indentation mechanically. If the Calvert and Johnson indenter is used in standard macro CI methods, it provides physical similarity conditions mechanically, over the entire macro depth range, minimizes SE, Fig. 7. The MCJ indenter generates almost the same specific contact surface area $X_{SV}(h) \approx const$, Fig. 6. Under the condition h >h*, the movement of the indenter in the MCJ has little effect on the macrohardness value. The effect of the relaxation region in this method is small. In MCJ , throughout the entire indentation process, the value of the specific energy expended on the formation of the material surface is approximately constant.

The use of different indenter displacement depth h in one-stage empirical standard methods for measuring the macrohardness number by a sphere and a pyramid leads to a violation of the physical conditions of similarity. In this case, the measurement of hardness is accompanied by an uncontrolled transition to another scale or to another physical measure of the process. The hardness number of the empirical method depends on h on the trajectory of the physical process CI, that is, the hardness number depends on the value of the function PHI(h), (9.6). Empirical hardness is the value of the function of the component of the specific generalized indentation power. The size effect arises when the condition of similarity of shape change is violated $X_{SV}(h) = const$.

Definitions of physical macrohardness of kinetic indentation.

The thermomechanical potential of the indented material $U_p = A(h)$ is a function of the state of the activated volume.**Physical macrohardness of the material** - $PHM(V, HB)$, dimension J/m^3, formulas (7), (7.1) , (7.2) different form of representation, specific potential of the generalized power of kinetic indentation, shape change of the activated volume of the material. $PHI_i(h, HB_i)$ - function of the potential component of the generalized specific power of indentation by the sphere, the potential gradient component is also a function of empirical hardness Fig.6, 7. The meaning and dimension of empirical and physical hardness are different. Formal translation of dimensions: $[J/m^3 = N/m^2 \times \frac{m}{m}]$. In Fig.6b there are two diagrams, for empirical $HI(h)$ and physical $PHI(h, HB, D_n)$ macro hardness, HB411, D5mm. Using the Brinell indenter as an example, the physical meaning and properties of the macro empirical hardness function CI, formula (9.6) and the essence of the surface macro indentation hardness numbers according to the ISO14577 standard are shown. Studies have shown that the methods for measuring the empirical macrohardness number of Brinell, Rockwell, Vickers, etc. according to the ISO14577 standard are incorrect from the standpoint of the physical theory of hardness. In empirical methods, there is no condition for the physical similarity of measuring the hardness number. The result of violation of the physical similarity of processes is the size effect. In [4], based on the physical approach, methods for comparing hardness values from different methods are considered. Using the dependences of physical methods for analyzing indentation, a virtual curve F(h) for the Vickers pyramid was analytically constructed, etc. Indentation is modeled as a process performed by a sphere with a variable diameter, a special function D(h) (dynamic Brinell ball) is set for this, etc.

The methods of mathematical modeling of the CI process, the function of the indenter shape from h is analytically given, showed the possibility of using physical theory to develop a universal program for comparing, converting hardness values of different standards and indentation methods.

Nano and micro indentation differs in its physical nature from the macro CI process [4]. Activation and shape change of the material occur in a very small volume of the body, the nano energy density is higher by an order of magnitude and more than in the macro range [16]. The nano process has its own physical function of the state of the activated volume [4]. With an extended CI range, for example, for indentation with a Vickers pyramid, two mechanisms of shape change and transformation arise in succession. The contribution of each of the body shaping mechanisms changes during the CI process. The basis of the theory of the indentation process in any range remains the physical concept - the specific power, the energy of the process of formation of the activated volume and the contact surface CI [4]. The assessment of physical nano-micro hardness by CI analysis for a sharp tool cone, pyramid, micro and nano sphere, is a separate method. The physical hardness diagram of indentation by a pyramid, a cone is performed using its own physical state function, on this basis a universal indentation equation was obtained [4], this is the topic of the next article.

Universal physical unit of macro hardness.

Taking into account the perfect theoretical foundation laid down in the Calvert-Johnson method, the prospect of applying the physical analysis of the CI results, we propose to use the universal physical unit of macrohardness in the standard:

$$1.CJ = 1 \cdot 10^7 J/m3 \qquad 1.CJ \text{ - one «caj».}$$

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 in the new standard in parallel, until the abolition of empirical methods.

Conclusions.

1. The physical characteristics of the experimental process of kinetic macroindentation of a material are theoretically substantiated: the function and number of physical hardness, the physical meaning and dimension of hardness are determined.

2. The function of the state of the activated volume of material for kinetic (instrumental) macro indentation by a sphere is determined.

3. Based on the analytical analysis of the standard kinetic force diagram, methods have been developed for determining the value of the physical potential of the macrohardness of a material, the function of the physical kinetic hardness of macroindentation. There is no size effect in the method. Universal physical hardness specifications have a number of important advantages and can replace empirical standard methods for measuring hardness.

4. The physical meaning of the standard empirical number of material macrohardness and the reason for the size effect in empirical macroindentation methods are shown.

5. An analytical relationship between the values of empirical and physical hardness of the kinetic macro indentation of the material has been established. Principles, similarity criteria and an analytical method for comparing the hardness numbers of materials for different sizes, tool shapes, in the range of macro indenation are formulated.

6. The results obtained form the basis for the development of an addition to the current ISO 14577 standard and the creation of a general physical theory of the hardness of structural materials in different ranges.

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