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Physical Macrohardness of the Kinetic Indentation of the Material: Function and Universal Unit of Measure (Part 1)

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Abstract: Three directions of development of kinetic indentation methods. Physical-energetic analysis of the indentation force diagram according to ISO 14577. Physical theory and universal criterion for the macrohardness of a material. Model of the physical process, thermomechanical potential, function of the state of the kinetic macroindentation process. Method for determining the physical function and unit of measurement of the kinetic macrohardness of a material. The ratio of the values of the empirical (standard) and physical macrohardness of the material. Physical reason for the appearance of the size effect in empirical indentation methods. The principle of determining the standard value of physical macrohardness.

Key words: Review, physical theory of kinetic indentation, method for determining physical macrohardness of the material.

1. Three Directions of Development of Indentation. Physical Concept of Hardness and Strength of a Material

1.1 Review, Conclusion

Modern indentation is a widespread multifaceted operational non-destructive method 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.

1.2 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

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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 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 Ref. [3]. Let us discuss the characteristic disadvantages of empirical indentation methods, using conclusions from the monograph of Professor V.I. Moshchenok [1] and the results of his own research. Let's consider the calculation of the hardness number by the Brinell method, within the framework of the ISO 14577-1:2002 standard [4]. In the method, there are more than thirty scales for measuring hardness; the hardness number depends on the force, but this dependence is not systematic. The American standard proposes the use of additional scales, thereby further complicating the method. There is no justified, clear criterion for choosing a scale for measurements, the obtained empirical values are systematized intuitively and experimentally, hardness depends on the diameter of the indenter. 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 lndentation Size 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 EH can be found in Refs. [1, 3].

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 the indentation creep, the indentation relaxation, 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 $F(h)$, see the example in Fig. 1c. 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 EH 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 phenomenological and empirical. 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.

1.4 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 Refs. [1, 3, 5-7].

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/m^3) 1-2 orders of magnitude higher than in the macro range. With an increase in the force and depth of kinetic indentation 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].

1.5 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 EH of the material. 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.

1.6 Physical Concept of Hardness and Strength of a Material

Hardness and strength are closely related to 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. Here is 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.

1.7 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, 8-10]. 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 Ref. [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

2.1 Scheme of the Macro Indentation Process

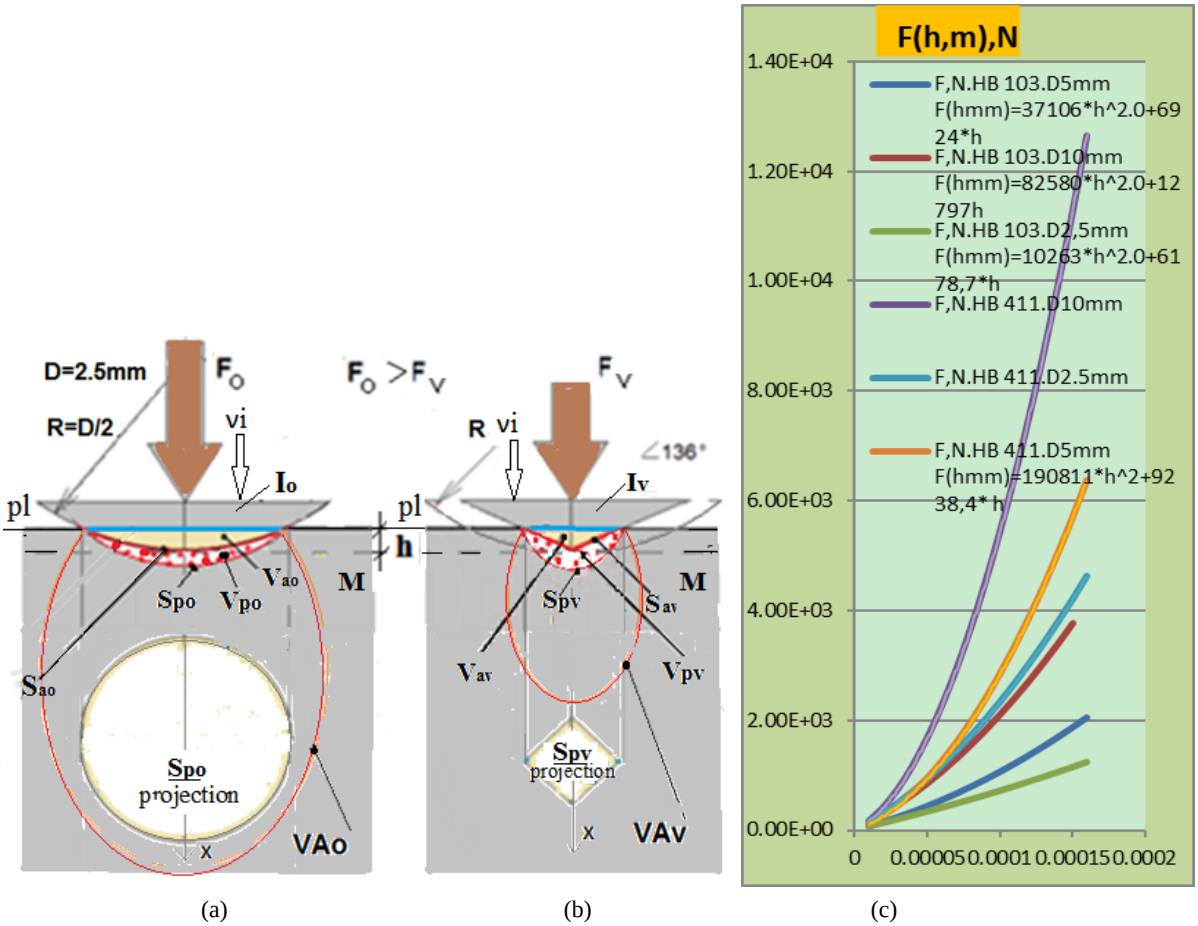
To develop a physical model of the macro indentation process, we first construct a scheme of the mechanical process using the example of two macro surface methods, indentation with a Brinell sphere and a Vickers pyramid (sharp indenter). In Fig. 1, designations are: M—material; I_o—spherical Brinell indenter, I_v—Vickers pyramid; Subscript: *o*—sphere, *v*—pyramid, *Fo* and *Fv*—force on the indenter; V_A—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 $V_a(h)$—the volume of the part of the indenter immersed in the material. Physical activated volume—V_p. 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. v_i, m/s, is the indenter speed. The volume V_p is limited by the surfaces S_a and S_p. It contains the material in a highly activated quasi-liquid state. S_a—the entire outer surface created by the indenter. S_p—conditional external boundary V_p of the volume. S_{ac} 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: S_{po}, S_{pv}. In this case, we take $Va(h) = Vp(h)$.

Considering the scheme of the process of indentation by the Brinell sphere in Figs. 1a and 1b, we formulate the concept of a thermomechanical system of elements: indenter-material-testing mechanism (source of force). Let us 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 V_p of the activated material volume.

2.2 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 V_p (Fig. 2), located between the contact surface S_a and the imaginary vortex wave surface S_p—the boundary of states with different structural and energy parameters of the material. In the volume V_p 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



(a) (b) (c)

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

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 Ref. [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. Fig. 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 V_p 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 S_p (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 S_p is denoted by the symbols ∂. This is the boundary of structural and energy transformations of the material during the formation of the volume V_p. All irreversible

processes of translational-rotational transformations of the structure of the initial state of the material occur on the outer surface S_p, 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 S_p, new internal state parameters of the structural units $\mathbf{P}_{\mathbf{p}}^{*}$, $\widehat{\mathbf{S}}_{\mathbf{p}}$, $\mathbf{T}_{\mathbf{p}}^{*}$ and translates these parameters into the volume V_p. To describe the state parameters of the physical volume V_p, 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 Ref. [13].

In the process of CI, in the activated volume V_p, material is accumulated with a new entropy value $\widehat{\mathbf{S}}_{\mathbf{p}}^{*}$. 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 $\mathbf{P}_{\mathbf{p}}^{*}= \sigma_{sh}^{*} = \text{const}$. In the external large volume V_{Ao}, 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 ø, homogeneous, stable process of transition of the source material to a new activated state has occurred in the layer ø. Thus, during the movement of a spherical indenter with a diameter D, with a certain small constant speed v_i, a continuous, stable, laminar process of movement, shape change, structural transformations and volume $V_p(h)$ growth occurs with parameters $\mathbf{P}_{\mathbf{p}}^{*}$,

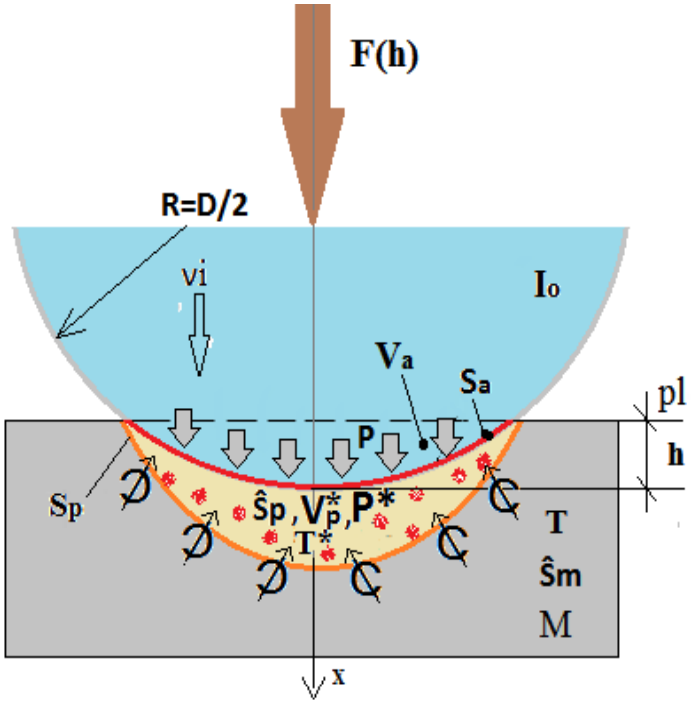


Fig. 2 Physical model of the activated material volume as a thermomechanical system.

$\widehat{S}_p$, T_p^*. Studies [1] have shown that to create such ideal conditions, a spherical indenter must have a diameter $D > D_{min}$, where, D_{min} 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 considering its physical properties.

2.3 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 us 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 ∂ in 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:

$$U = Q - A \quad (1)$$

where, U (J) is the potential of the internal energy of the thermodynamic system; Q is heat energy transferred to the system; A is the work done by external forces on the system.

$$A = \int P dV, \; Q = \int T d\widehat{S}. \quad T = \text{const}, \; P = \text{const} \quad (2)$$

From Eqs. (1) and (2), taking into account the accepted notation for the activated volume $V_p(h)$:

$$U_p = T_p^* \widehat{S}_p^* + P_p^* V_p^* \quad (3)$$

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

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 Eq. (1) 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 us 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.

2.4 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 Ref. [14], the volume potential differential U_p in Eq. (4) is the limit of the ratio of the energy increment and the activated volume increment:

$$\frac{dU_p}{dV} = \frac{d(T_p^* \widehat{S}_p^* + P_p^* V_P^*)}{dV}, \quad T^* = \text{const}, \quad P^* = \text{const}. \quad (4)$$

Let us denote this volume differential of the energy increment:

$$PHM(V_p) = \frac{dU_p}{dV} \quad (5)$$

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 v_i are unambiguously interconnected quantities, the process time and the indentation volume are one-to-one. Therefore, we can use for Eq. (5) PHM(V_p)—the term generalized specific power of energy change per unit of activated volume. Briefly Eq. (5) 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 from Eq. (5) 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 Eq. (3), the entropy and temperature of the increasing volume V are constant values $\widehat{S}_p^* = \text{const}$, $T^* = \text{const}$, 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:

$$U_p = P_p V_p = A(V) \quad (6)$$

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:

$$A(V) = A(h) = \int_0^{h_o} F(h)dh \quad (7)$$

$$A' = \partial A / \partial h = F(h) \quad (8)$$

$$U_p = \int_0^{h_o} F(h)dh \quad (9)$$

In what follows, we assume $V_p = V_a$; for simplicity of notation, we omit the subscript $V_p = V_a = V$. Using Eqs. (2), (4), (6), we obtain the volumetric differential, let us call its potential the specific generalized power of macro indentation of the material:

$$PHM(V) = \frac{dA(V)}{dV}, \quad (10)$$

According to the general field theory [14], the potential of the specific indentation power in Eq. (10) is related to the gradient of the energy field density on the surface of the activated volume:

$$PHM(V) = \text{grad}A = \frac{\partial A}{\partial V_x} + \frac{\partial A}{\partial V_y} + \frac{\partial A}{\partial V_z} =$$

$$PHI_x(h) + 2PHI_z(h) \quad (11)$$

where, $\text{grad}A$ is the gradient $A(V)$ on the surface S_a of the activated volume $V(h)$,

$$PHI_x(h) = \frac{\partial A}{\partial V_x}, \quad PHI_y(h) = \frac{\partial A}{\partial V_y}, \quad PHI_z(h) = \frac{\partial A}{\partial V_z},$$

$PHI_y(h) = PHI_z(h)$, $PHI_{x,y,z}(h)$ of the potential A gradient along the axes of Cartesian coordinates. Let us apply the physical definition to the specific power potential $PHM(V)$, in Eq. (11)—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 Eq. (11) is the total specific generalized power

of the energy density flux through the surface of the activated material volume V in the CI process.

2.5 Experimental Properties of the Potential of the Specific Generalized Indentation Power. Physical Standard of Macrohardness

In Ref. [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 $A(V, m^3)$. Fig. 3 shows the functions A (V, m^3), the integral of the function $F(h)$. Standard measures of hardness, sphere diameter D10/5/2.5 mm [2] were studied: Fig. 3 a, b Measures HB103/411, measurement range h = 0.1-033 mm; Figs. 3c-3f show measure HB176, range h_{max} = 0.5-5.0 mm. 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, as the example in Fig. 3, Eq. (10) was analytically determined, also 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:

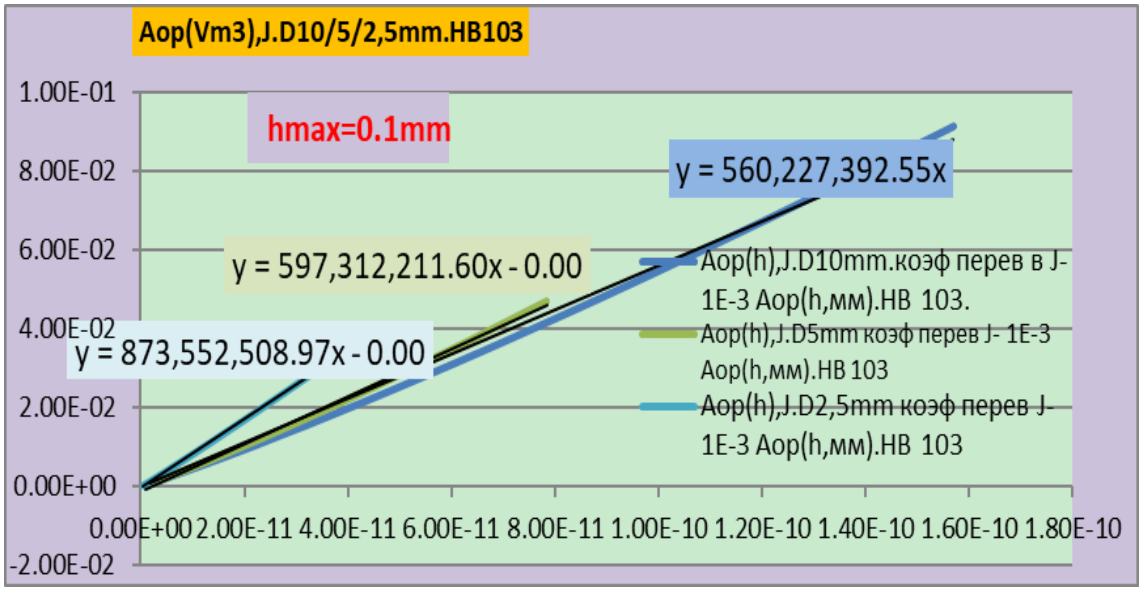
$$\mathrm{PHM(HB)} = A'(V)_v = \frac{\Delta A}{\Delta V} \approx \frac{dA}{dV} = \mathrm{const} \quad (12)$$

where, $A'(V)_v$ is the parameter of the linear trend of the function, according to Eq. (10) 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 $\mathrm{PHM(HB)}$ of different hardness measures are in Table 1.

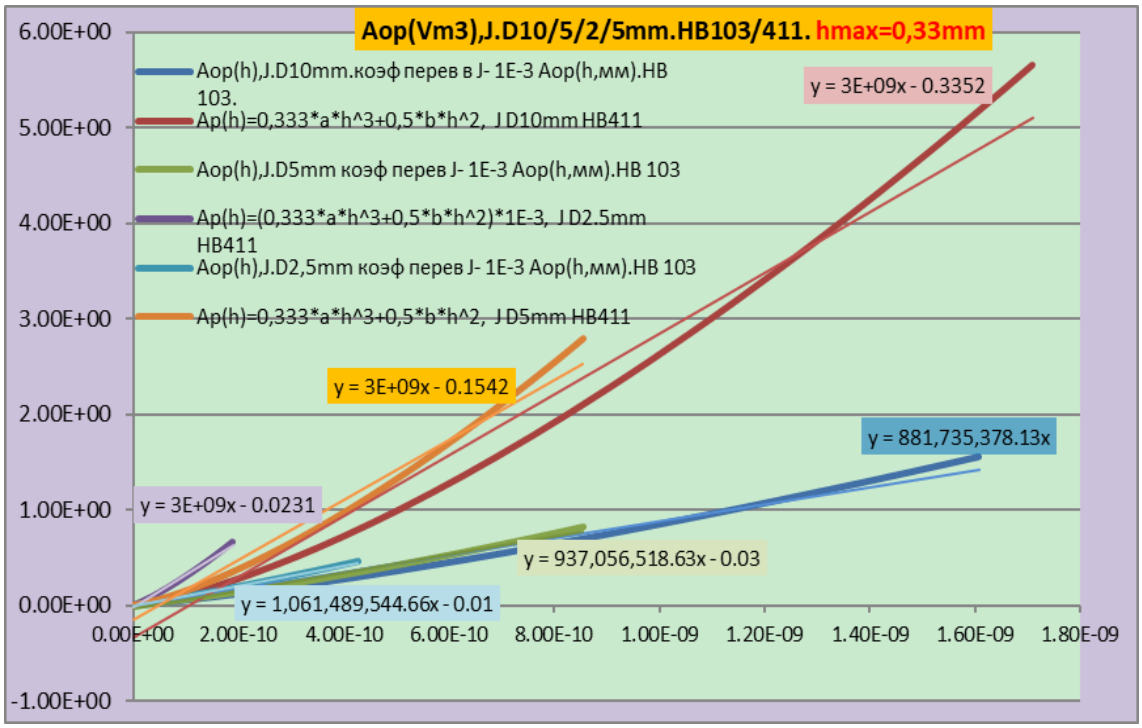
From Eq. (10) and the results of the analysis of experimental data, it follows that the thermomechanical potential over a large interval h is a linear function:

$$A(V) = \mathrm{PHM(HB)} \cdot V_a = A'(V)_v \cdot V_a \quad (13)$$

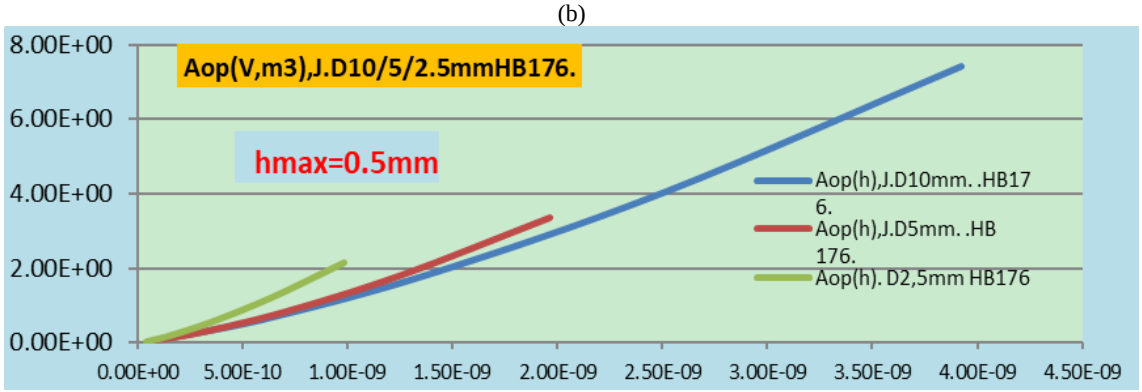
Physical hardness, according to the results of indentation of a standard measure with a sphere is shown in Table 1.



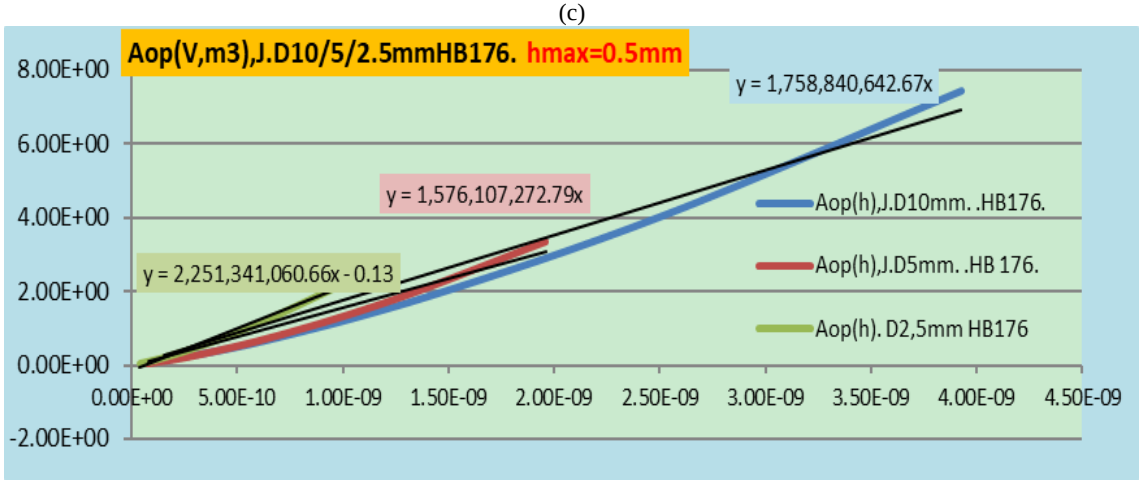
(a)


Aop(Vm3),J.D10/5/2/5mm.HB103/411. hmax=0,33mm
Aop(h),J.D10mm.коэф перев в J- 1E-3 Aop(h,мм).HB 103.
Ap(h)=0,333*a*h^3+0,5*b*h^2, J D10mm HB411
Aop(h),J.D5mm коэф перев J- 1E-3 Aop(h,мм).HB 103
Ap(h)=(0,333*a*h^3+0,5*b*h^2)*1E-3, J D2.5mm HB411
Aop(h),J.D2,5mm коэф перев J- 1E-3 Aop(h,мм).HB 103
Ap(h)=0,333*a*h^3+0,5*b*h^2, J D5mm HB411
y = 3E+09x - 0.3352
y = 3E+09x - 0.1542
y = 881,735,378.13x
y = 3E+09x - 0.0231
y = 937,056,518.63x - 0.03
y = 1,061,489,544.66x - 0.01
6.00E+00
5.00E+00
4.00E+00
3.00E+00
2.00E+00
1.00E+00
0.00E+00
-1.00E+00
0.00E+00
2.00E-10
4.00E-10
6.00E-10
8.00E-10
1.00E-09
1.20E-09
1.40E-09
1.60E-09
1.80E-09

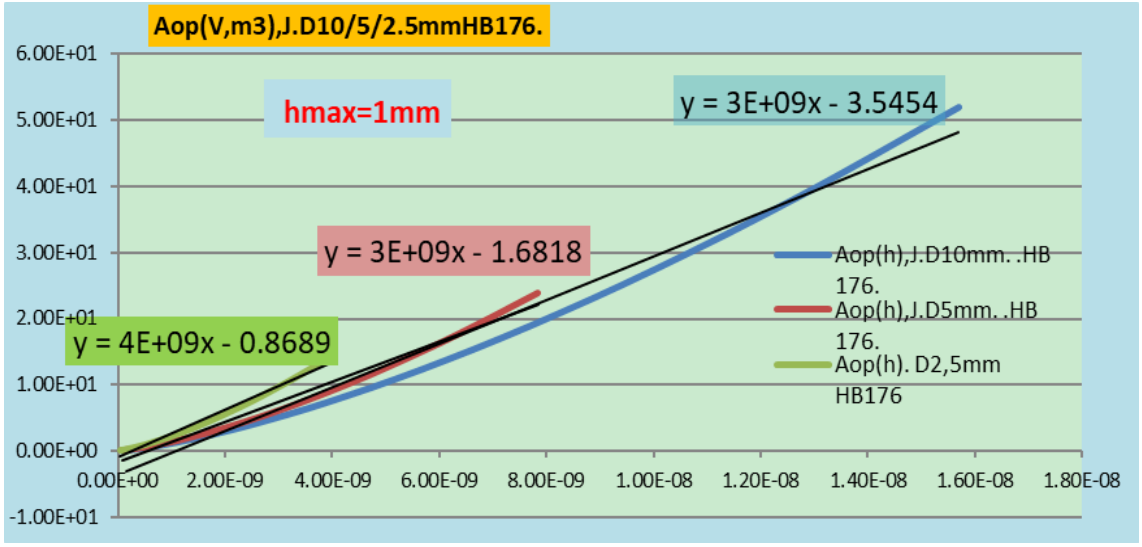
(b)


Aop(V,m3),J.D10/5/2.5mmHB176.
hmax=0.5mm
Aop(h),J.D10mm. .HB176.
Aop(h),J.D5mm. .HB 176.
Aop(h). D2,5mm HB176
8.00E+00
6.00E+00
4.00E+00
2.00E+00
0.00E+00
0.00E+00
5.00E-10
1.00E-09
1.50E-09
2.00E-09
2.50E-09
3.00E-09
3.50E-09
4.00E-09
4.50E-09

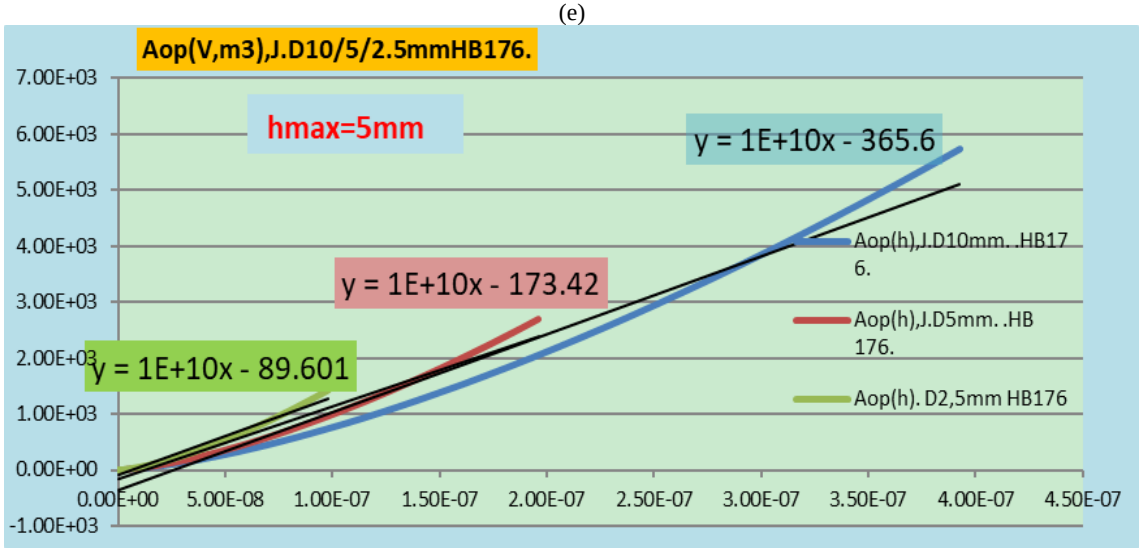
(c)


Aop(V,m3),J.D10/5/2.5mmHB176. hmax=0.5mm
y = 1,758,840,642.67x
y = 1,576,107,272.79x
y = 2,251,341,060.66x - 0.13
Aop(h),J.D10mm. .HB176.
Aop(h),J.D5mm. .HB 176.
Aop(h). D2,5mm HB176
8.00E+00
6.00E+00
4.00E+00
2.00E+00
0.00E+00
-2.00E+00
0.00E+00
5.00E-10
1.00E-09
1.50E-09
2.00E-09
2.50E-09
3.00E-09
3.50E-09
4.00E-09
4.50E-09

(d)



(e)



(f)

Fig. 3 Approximation of the potential $A(V, \text{m}^3)$ kinetic laminar macro indentation. Indenter sphere $D10/5/2.5$ mm. The equation and linear trend $A'(V)_v$ parameter for each function is shown. Excel 2007 was Used: (a) 1.2 standard hardness test blocks HB103/411, range h_{max} = 0.1 and 0.33 mm; (b) 1,2,3,4 HB 176. range h_{max} = 0.5/1.0/5.0 mm. Experimental diagrams $F(h)$ are from Ref. [3].

Table 1 Physical hardness, based on the results of indentation of a standard measure with a sphere

Standard measure of hardness	Mean physical hardness of indentation PHM(HB), J/m^3	Physical hardness values for indentation hardness test blocks HB103/176/411, diameter 10/5/2.5 (D, mm), PHM(HB)=$A'(V)_v$, J/m^3		
HB 411	3.2×10^9	3.1×10^9 (D, 2.5)	3.1×10^9 (D, 2.5)	3.4×10^9 (D, 10)
HB 176	1.85×10^9	2.23×10^9 (D, 2.5)	1.58×10^9 (D, 5)	1.76×10^9 (D, 10)
HB 103	0.94×10^9	1.0×10^9 (D, 2.5)	0.94×10^9 (D, 5)	0.89×10^9 (D, 10)

3. 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 Eq. (12) and the activated volume V_a. Another formulation of dependence Eq. (13): the volume potential of the activated volume of macrolaminar indentation $A(V)$, is equal to the product of the specific generalized indentation power potential Eq. (10) 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 in Eq. (12). 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 $0.1 < h < 0.33$ mm 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/m^3. 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 Ref. [7], in which it was proposed to use the specific indentation energy as an indicator of material hardness. In Ref. [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 Ref. [1].

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