Part 2.5

2.5 Physical parameters of the cyclic diagram F(h) MKI, a new effective method of diagram analysis for determining the hardness number on the Brinell scale. Examples of hardness calculation. Conclusions.

ABSTRACT

Let us consider an analytical method for determining the hardness number on the Brinell scale, based on the physical analysis of the cyclic diagram. Using examples, we will show the general physical properties of the cyclic diagram, the prospects for the expanded application of the physical method of analysis, for solving applied problems of strength, hardness, damage to materials. The generalized rate of force growth is a hardness criterion for the cyclic indentation process.

Plan.

2.5.1. Statement of the problem. CYMKI diagrams obtained on UTM−20HT ISP NANU, physical analysis of the construction method.

2.5.2. . Universal physical method for calculating the empirical Brinell hardness number HBW using the physical parameter of the linear trend of the experimental cyclic diagram of the function F(h). Table of CYMKI parameters and process parameters of the MCJ standard.

2.5.3. Comparison of physical parameters of two versions of CYMKI diagrams. Analysis of parameters in one cycle in the area of active growth of force and displacement.

2.5.4. Generalized indentation rate - a universal integral criterion of hardness in CYMKI. Relationship between the measure, the unit of measurement of the hardness scale and the parameter k_{fh} , N/m, (linear trend) of the generalized rate MKI.

2.5.5. Examples, calculation of HBW hardness of steels according to CYMKI diagram, sphere indenter D 2.5 and 0.76 mm.

2.5.6. Discussion. Conclusions.

2.5.1. **Statement of the problem. CYMKI diagrams obtained on UTM−20HT ISP NANU, physical analysis of their construction method.**

Let us consider a simplified analytical method for determining the hardness number on the Brinell scale, based on the physical analysis of the cyclic diagram F_{cycle}(h) MKI, for this purpose we will use experimental sphere indentation diagrams obtained by ISP NANU [14,19], example Fig. 5. Let us consider the principles and features of this physical method of hardness testing. Let us discuss the general physical properties of the cyclic diagram and the prospects for the expanded application of the physical method of their analysis for solving applied problems of strength, hardness, and damage to materials.

Let us analyze the physical properties and parameters of the cyclic diagram of kinetic macroindentation (hereinafter CYMKI) $F_{cycle}(h)$, $h_{cycle}(t)$ of steels, example Fig. 5; 6. The diagrams were obtained in ISP NANU [14,19], on the UTM-20HT machine, to create an empirical correlation method for estimating hardness on the Brinell scale based on CYMKI data. As a result of these studies, an improved method for testing the hardness number on the Brinell scale was developed based on CYMKI [19]. The advantage of the CYMKI - ISP NANU method is that the complex stage of measuring the parameters of the spherical indenter imprint in the material was excluded. The method is empirical, because it analyzes only the external parameters of the MKI process, there is no theoretical justification for the physical meaning of the studied process and there is no physical measure of the hardness number. This circumstance is due to the fact that the HBW hardness value initially has no physical meaning, it is a correlation characteristic. The method is based on the experimental search for a correlation between the average value of the empirical parameter a (the slope tangent of the function F(h), Fig. 8) and the hardness number HB a priori established on the tested standard. Measurements of the desired number a (the correlation parameter of hardness) are performed in each cycle of the diagram and then averaged by analyzing the diagram b.

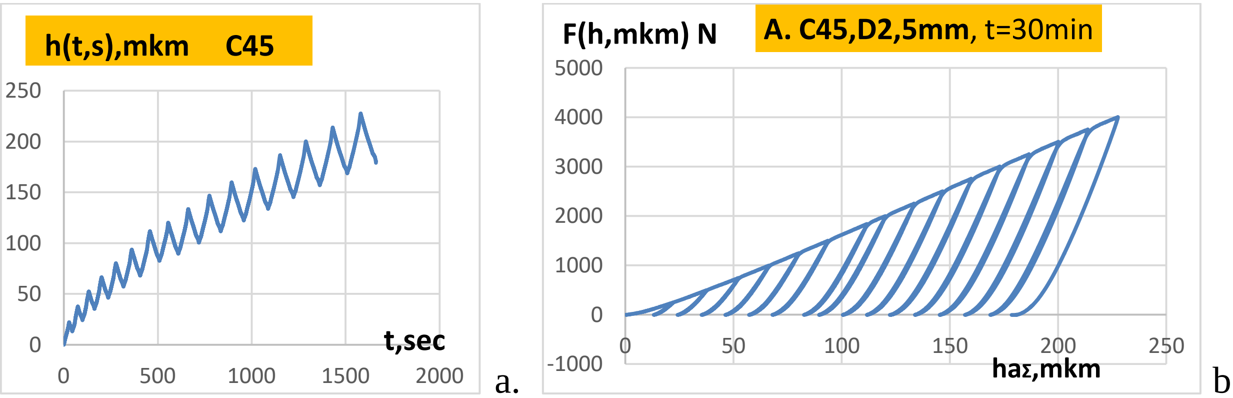
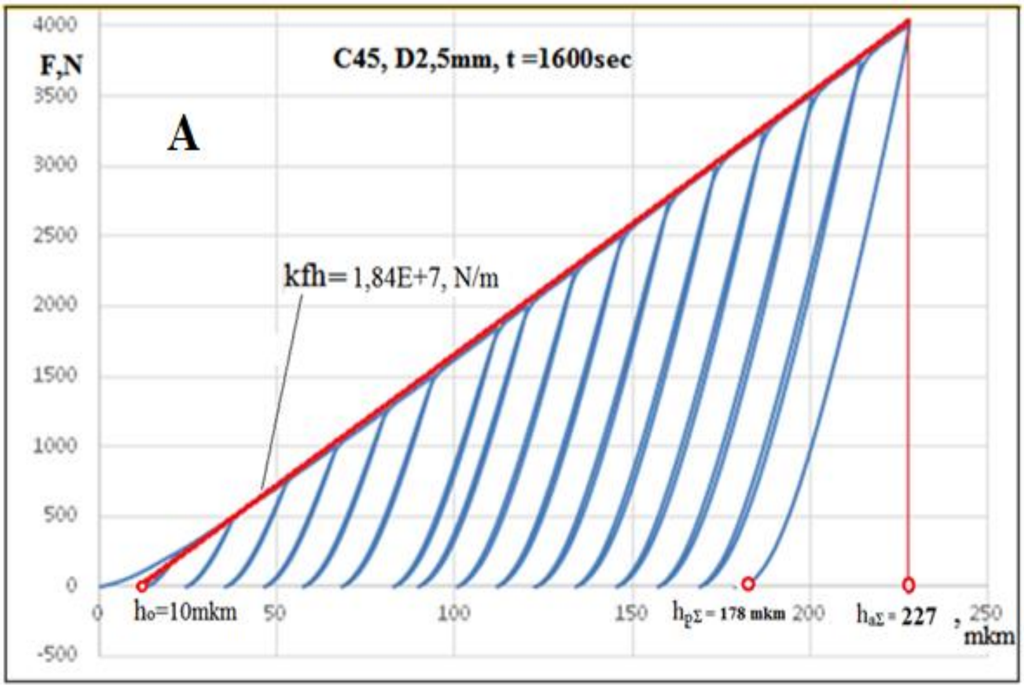


Fig. 8 Results of MKI experiments steel C45, sphere D2.5mm, IPS NASU [14]: a). Diagram h(t) cycle, b) . Diagram F(h), option A.

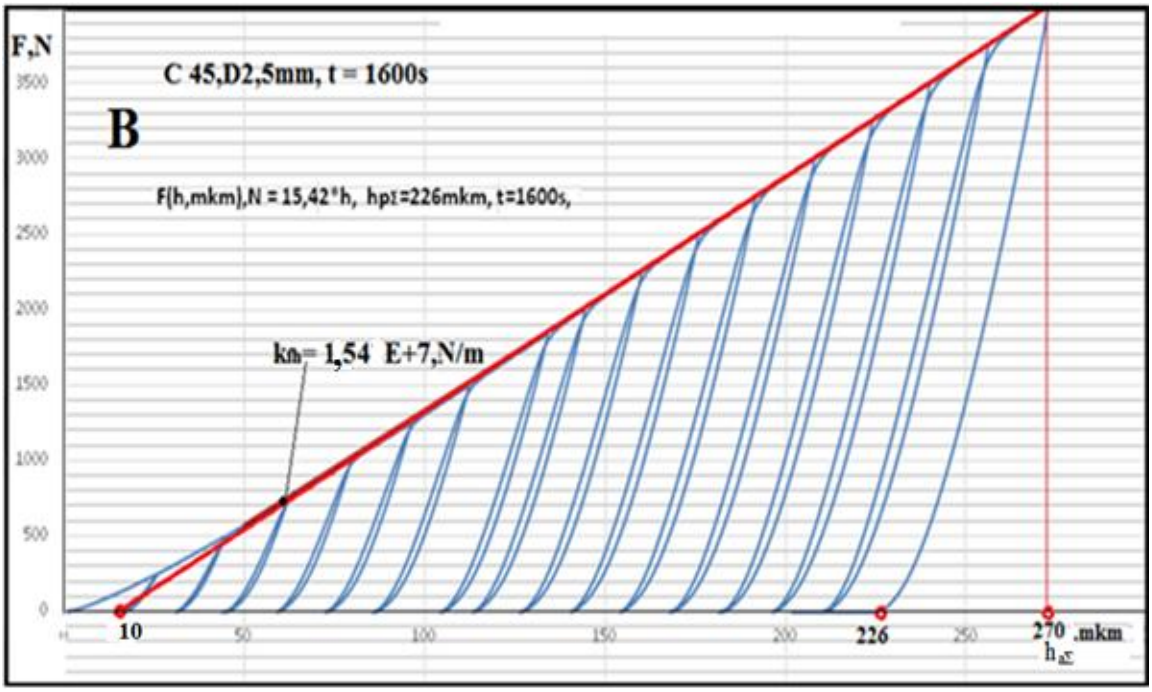
Experimental diagrams of hardness testing, based on CYMKI data, were obtained at ISP NASU in Kyiv, published in [19], some of the material was kindly provided to me by the head of this research. These data allowed us to perform a deep physical analysis of different diagrams. On this basis, a universal physical theoretical criterion and method for analyzing the hardness function were developed and tested. As a result, the foundations of a universal method for analyzing the indentation diagram F(h) were created. The methods are applicable for a single-act process, as well as for CYMKI MKI processes.

First, let us consider the general properties and physical meaning of the main CYMKI parameters, the principles that the physical analysis and method use.

Let us compare two different diagrams of CYMKI tests, A and B, for steel C45, Fig. 6. For comparison, the parameters of the two MKI test variants (A,B) are shown in Table 3. In the calculations of the material hardness, the data of the MKI experiments of steel C45, sphere D2.5mm from [14] and additional experimental diagrams CYMKI ISP NASU were used



a.



b.

Fig. 9. Comparison of two cyclic diagrams MKI Fcycl (h), with different generalized velocity kfh, N/m, steel C45, sphere D2/5mm: a) variant A of the diagram, trend kfh $= 1{,}84E + 7$, initial Fig. 5b; b) diagram B with the changed parameter of rheological velocity dh/dt, m/s. In red - the envelope line of all sections of the linear trend F(h) of the cyclic diagram, constructed on each cycle of active growth of force by the value $\Delta F_i = 250, N$. The diagrams were obtained on UTM−20HT, ISP NASU [14].

Additional diagrams CYMKI were obtained in the process of intuitive search for the necessary correlation parameters of the method [19] ISP NASU. This method uses a sequential iterative experimental search for the correlation parameter a. The search was performed on the experimental setup UTM−20HT and others. Parameter a is the tangent of the slope of the linear trend a = tg(γ), on a small section of active growth ΔFi , Δhi of the new cycle of the diagram F_{cycle}(h), (Fig. 8,9). In each cycle, a certain mechanical process is automatically simulated, then the machine repeats the specified physical and mechanical parameters in the next cycle. These parameters ensured a stable correlation of the sought hardness number of the material and the hardness number of the standard (hardness measure) installed on the tested material. The method does not contain a theoretical basis, and initially there is no model of the physical process of indentation. The ISP NASU method does not formulate the criterion of similarity of the physical process, there is no correct definition of the key initial physical process that was used to determine the hardness of the standard. In the empirical approach, there is historically no definition of the standard of the physical and mechanical process of indentation. The simplified ISP NASU hardness testing method is based on the formal equality of two values HBW $=k_n$*a , where k_n is the normalization parameter. As a result of testing by this method, a correlation was established between the hardness number of the standard HB and the value of the experimental parameter a = tgγ on the cyclic diagram MKI.

Now let us consider the physical aspects of CYMKI - ISP NASU. Parameter a is determined on each cycle of the diagram, at h > ho, Fig. 7. As a result of automation of the MKI process, the ratios of the main mechanical parameters of the cycle necessary for correlation are selected. In particular, during testing the rate of growth per cycle of force - ΔFi, the speed of displacement - Δhi are controlled. The time of the full cycle is Δthr, the full amplitude of movement for the full cycle is HRi, the time of the active cycle is Δti, etc. The measurement data of the parameter a for 16 cycles are processed by the statistical method. As a result, the average parameter a is proportional to the required accuracy of the hardness number HB of the standard. This is briefly the essence of this method, the ISP CYMKI correlation, it allows finding the material hardness number on the Brinell scale more simply than the standard ISO 6506-1 method. The CYMKI - IPS NASU method has expanded the possibilities of creating and using mobile devices for measuring the actual empirical hardness number of a material directly in the elements of an operating structure [19].

In the works [1,2,3.4, 15] it is shown that the HBW hardness number itself on the standard initially does not have a correctly substantiated physical meaning, both as a value and as a physical measure. Basically, hardness is a dimensionless quantity. The physical meaning of the material hardness value, the algorithm and the measure (unit) of measurement were lost. In my opinion, this happened after 1870, during the transition from the fundamental physical method of measuring hardness Calvert Johnson (MCJ) to subsequent methods that utilitarianly improved the technology and violated some important principles of the first correct tests. More details about the MCJ method Part 2.5 and [3,4]. These changes made subsequent hardness testing methods physically incorrect, uncontrolled errors, ISE, etc. arise or persist in measurements. The above largely applies to the CYMKI - IPS NASU hardness number determination method.

2.5.2. *Universal physical method for calculating the empirical Brinell hardness number HBW using the physical parameter of the linear trend of the experimental cyclic diagram of the function F(h). Table of CYMKI parameters and process parameters of the MCJ standard.*

The CYMKI - ISP NASU methodology contains a number of important principles that can be preserved and applied when implementing new correct, universal promising physical methods of hardness testing. The CYMKI experimental diagrams allow for a detailed analysis of the main physical parameters of the MKI process and to show their relationship with the parameters and criteria used in the fundamental measurement method and the MCJ hardness scale.

Let us apply the generalized indentation rate concept $k_{fh}(h,H) = \upsilon_{fh}(h,H) = F'_h(h) = \partial F / \partial h$ (9.3) in the physical method of analyzing the F(h) diagram and construct a common (envelope) straight trend line for all 16 cycles (Fig. 6). The results of applying this method for calculating the hardness of steels in Brinell units HBW were published in the article [3].

Let us study the CYMKI experimental diagrams of steels F (h), Fig. 8,9 using physical methods of analysis and determination of the hardness of materials [3,4]. Let us determine the HBW hardness number on the Brinell scale using a physical method, using for this the F(h), h(t) diagrams of hardness testing obtained by ISP NASU. This is necessary to demonstrate the physical calculation method and confirm the physical theory of hardness. Thus, we will confirm that the physical method has a theoretical basis, which contains the main physical principles that were created and used in MCJ [16].

Fig. 8 shows the diagrams of tests of steel C45, sphere D2.5mm: h(t,s) mkm; F(h,mkm),N. Fig. 5a - diagram of indentation h(t), variant A, total process time tΣ= 1660 sec; (28min) - exposure of the full cyclic process, this is the total time for 16 cycles, with unloading pauses and growth cycles ΔFi. Fig. 9a,b show different in parameters diagrams A and B of cyclic growth of force F(h) acting on the indenter → Fcycle(h) during the tests. In both cases, the same maximum force Fmax $= 4 \cdot 10^{3}$, N accumulated over 16 cycles. Variants A, B were obtained for 16 cycles with different total accumulated plastic - hpΣ , total elastic-plastic deformation - $h_{a\Sigma}$:

$hB_{maxa}\Sigma > hA_{maxa}\Sigma$. $hA_{maxa}\Sigma = 227$mkm . $h_{Bmaxa}\Sigma = 270$mkm

Depth h_o is the initial section of the diagram, relaxation of the interaction of the material and the indenter, on it there is a substantially nonlinear process, tuning and reaching the required parameters occurs. Then comes the mode with a constant value of the generalized rate of force growth - $_{kfh,}$ N/m at the active phase of indentation MKI for each cycle.

Designations: $h_{a\Sigma}$, mkm - total (accumulated) elastic-plastic displacement of the indenter. This is the value of the indenter displacement at the end of the 16th cycl.

$h_{p\Sigma} = \Sigma\Delta h_{p\Sigma}$, mkm - accumulated total amplitude of accumulated plastic cyclic displacements of the indenter for 16 cycles

Test variant A. $h_{p\Sigma}$ =178mkm, $h_{pe\Sigma} = h_{a\Sigma}$ = 227mkm

Test variant B: $h_{p\Sigma}$ =227 mkm, $h_{pe\Sigma} = h_{a\Sigma}$ = 270mkm

=16*$\Delta h_{p\Sigma}$ = 178 mkm - total amplitude of accumulated plastic cyclic displacements.

Table 3 shows the parameters of the A, B diagrams of cyclic macroindentation of steel C45. It also shows the parameters of the single-act MKI process MCJ method. From the comparison it can be seen that the main parameters $\upsilon_{Rh} = \Delta h_i / \Delta t_i$ and $k_{fh} = \Delta F_i / \Delta h_i$ N/m of the MKI CYMKI process of testing the hardness of materials on the Brinell scale with a

D2.5mm sphere, on the UTM−20HT testing machine, ISP NASU [14, 19] are approximately equal to the main parameters in the fundamental MCJ method.

Table 3. Main parameters of the diagrams of cyclic macroindentation of steel C45 and parameters of single-act indentation of steel by the MCJ method.

parameter / variant	Fmax, N / ΔFi., N	N cycle	$h_{a\Sigma}$, mkm	$h_{p\Sigma}$, mkm	$\upsilon_{Rf} = \Delta F_i / \Delta t_i$, N/s	$\upsilon_{Rh} = \Delta h_i / \Delta t_i$, mkm/s	k_{fh} N/m
A $F_{cycl}(h)$	$\frac{4\cdot10^3}{250}$	16	227	178	27,5	1,49	1,84E+7,
B $F_{cycl}(h)$	$\frac{4\cdot10^3}{250}$	16	270	226	26	1,69	1,54E+7,
MCJ, $F(h)_{act}$ Fig.12b;13a	$\frac{3{,}92\cdot10^4, N}{-}$	1	Δh_{max} 3250	Δhp 3000	25,0	$\overline{\upsilon}_{Rhi.CJ}$ 1,8	ki_{fhCJ} $Fi_{max} / \Delta hp$ $1{,}31\cdot10^7$

* *The parameters of the rheological velocity CYMKI are highlighted in blue.*
$\overline{\upsilon}_{Rhi.CJ}$ - *average generalized velocity MCJ.*

3. Comparison of the physical parameters of two versions of the CYMKI diagrams. Analysis of the parameters in one cycle in the area of active growth of force and displacement.

Fig. 9 shows two diagrams, built in Excel (punctual type), the abscissa axis is $h_{a\Sigma}$ the sum of the accumulated cyclic elastic-plastic deformations, in this case it is an independent value for the Fcycl function ($h_{a\Sigma}$). The linear trend of the envelope Fcycl ($h_{a\Sigma}$) is shown (in red), it is formed by combining the conditional lines of the inclined sections a-b-c for 16 cycles Fig. 10. The general line is formed from the sections ΔFi-Δhi of active growth of force. Thus, for the entire diagram, the trend k_{fh}=Fmax/$h_{a\Sigma}$ is formed. The details of each complete cycle, the analysis of the parameters, at the stage active growth (SAG) of the force ΔFi, are shown in Fig. 10, 11.

In Table 3, the main parameters of the diagrams A, B of cyclic macro indentation of steel C45. Parameters MKI for MCJ, the steel does not have an exact grade.

Further comparative analysis of physical and mechanical parameters of MKI processes in two variants of cyclic indentation A, B Fig. 10,11.

Option A. Fig. 9a According to (9.10), (9.11):

$$\upsilon_{Rf}(h,t) = F_t'(h) = \frac{dF}{dt} \approx \Delta F / \Delta t \quad . \text{N/m}$$

Where, $\upsilon_{Rh}(h,t)$ is the growth rate of the indenter force acting on the material.

$\upsilon_{Rh}(h,t) = h' = x' = \partial h / \partial t$, m/s

Where, $\upsilon_{Rh}(h,t)$ is the velocity of indenter movement. Let us further designate specifically:

$\upsilon i_{Rf}(h,t)$ -- rheological growth rate of force F in the SAG section of the KI cycle
$\upsilon_{iRh}(h,t)$ -- rheological growth rate of movement during the active period of the SAG indentation cycle , (linear growth section of F(h), Fig.10):

Average conditional velocity of indenter movement (including the process time in the pause sections SYNCYCL):

$$\upsilon_{iRh} = h_{p\Sigma} / t_{max}, m/s \quad \upsilon_{iRh} = 178 \cdot 10^{-6} / 1660 = 0{,}107, mkm/s$$

Generalized average force velocity for SAG indentation Fcycl(haΣ), SYNCYCL time excluded:

$$k_{fhcycle} = F'_{h\ cycl} = \frac{F_{max}}{\Delta h_{\Sigma}} = \frac{4000N}{217 \cdot 10^{-6} m} = 1{,}84E+7, N/m$$

где, $\Delta h_{\Sigma} = h_{a\Sigma} - h_0$. $h_{a\Sigma} = 227mkm.$ $h_0 = 10mkm$

$$\Delta h_{\Sigma} = 227 - 10 = 217mkm$$

The Fcycl (haΣ) diagram, Fig.6.7.8, is constructed in Excel format, punctual. The value haΣ in this case is an independent variable.

$$ha\Sigma = 227 \cdot 10^{-6} m\ , \quad \Delta ha_{1cycl} = \Delta h_{a\Sigma} / 15cycle = (226 - 10) \cdot 10^{-6} m / 15 = 14{,}4 \cdot 10^{-6} m$$

B variant. Fig. 9b. This variant was obtained in the process of setting up the parameters for measuring the hardness on the HBW scale of steel C45 by the CYMKI ISP NASU method. In this variant of CYMKI testing, the main principle necessary for maintaining the similarity of the MKI process, which was used in the fundamental MCJ method, is not followed. In particular, an incorrect speed is used $\upsilon_{Rh}(h,t)$. Let us consider the features of the physical parameters of the testing diagram.

$$\Delta h_{\Sigma} = h_{a\Sigma} - h_0\ .\ h_{a\Sigma} = 270mkm.\ h_0 = 10mkm$$

$$\Delta h_{\Sigma} = 270 - 10 = 260mkm$$

$$ha\Sigma = 270 \cdot 10^{-6} m\ , \quad B.\ \Delta ha_{1cycl} = \Delta h_{a\Sigma} / 15cycle = (270 - 10) \cdot 10^{-6} m / 15 = 17{,}3 \cdot 10^{-6} m$$

Average rheological velocity of movement in the SAG section of growth of Δhi in one KI cycle without subtracting the effect of SYNCYCL (false velocity):

$$\overline{\upsilon}_{iRh} = \Delta h_{\Sigma} / \Delta t = 211 \cdot 10^{-6} m / 1660 s = 0{,}134 mkm / s = 0{,}13 \cdot 10^{-6} m / s \,.\, \mathbf{\Delta t} = 1660 sec.$$

As a result, we obtain the parameter of generalized velocity for variant B:

$$k_{fh} = F_{max} / \Delta h_{\Sigma} = 4000, N / 260 \cdot 10^{-6} m = 1{,}54 \cdot 10^{7}, N / m$$

Fig. 10, test variant A, shows a fragment of the diagram in cycle 16 in the SAG section of the force by the value $\Delta F_i = 250, N$, at the same time there is an increase in the elastic-plastic Δh1 and plastic Δh2 movement of the indenter, Δhi = Δh1+Δh2.

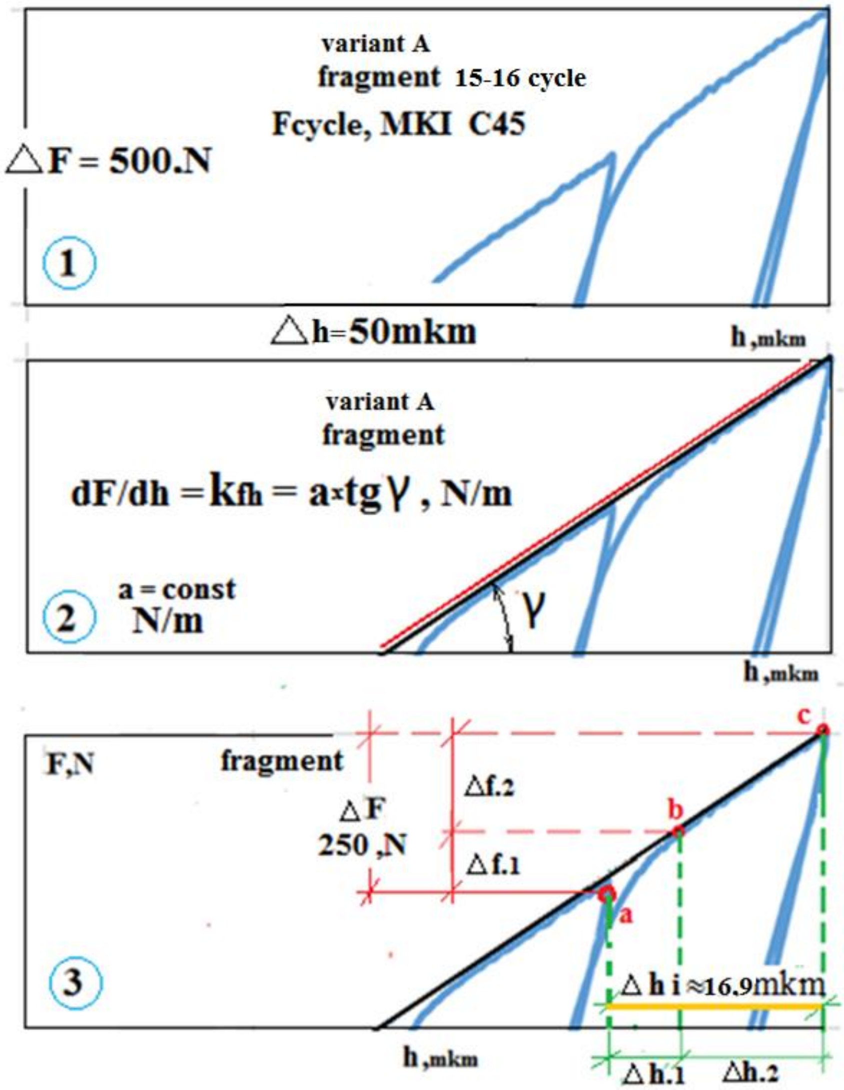


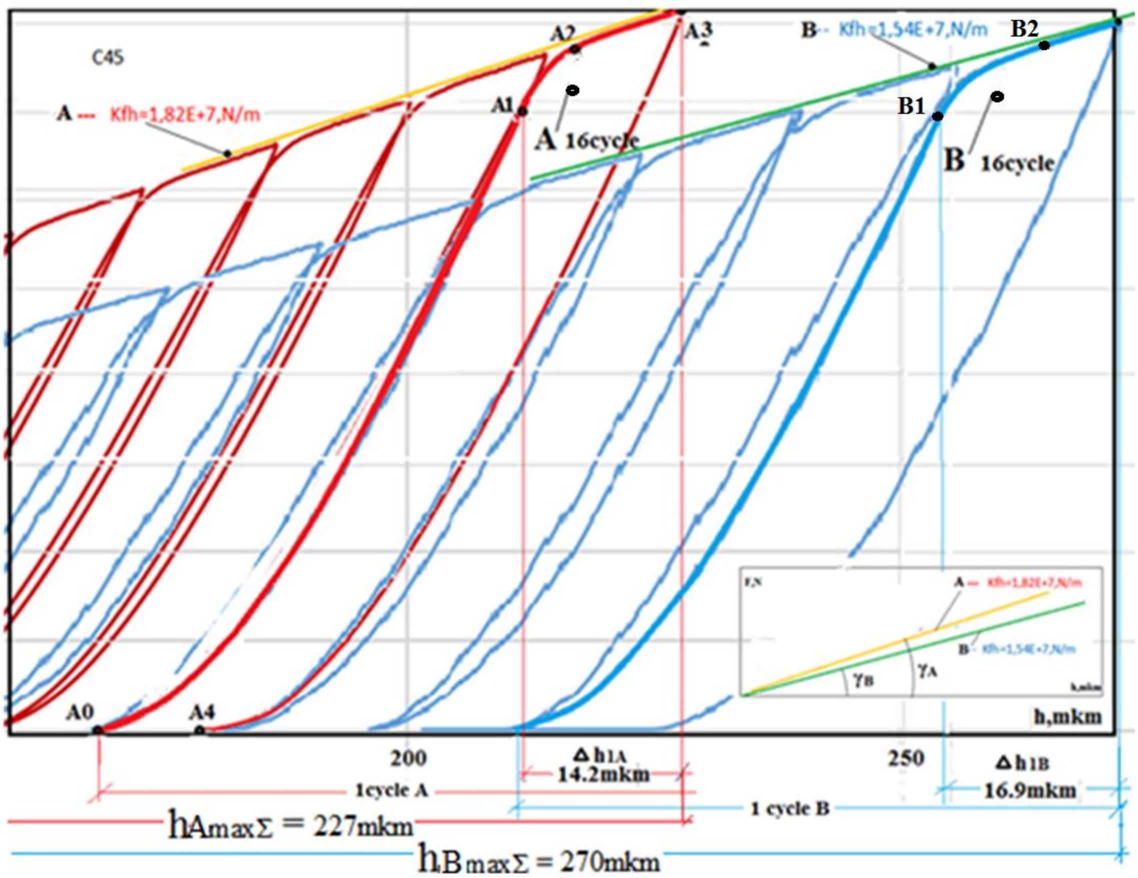
Fig. 10. Analysis of the main elements of the MKI process at the SAG stage of force ΔFi and displacement Δhi in one cycle. Accumulation and growth of plastic deformation: Δhi = Δhepl – step of total displacement and activation of irreversible deformation, Δh.1 – elastic-plastic stage (a-b), Δh.2. – plastic stage (b-c).

At each new cycle of indenter displacement Δhi, accumulation and growth of the total value haΣ of elastic and irreversible deformations occurs. In the Fcycl diagram, the SYNCYCL sections (reverse and return) are shown as curves of growth and decrease of force F(h). Fig. 10 schematically shows the formation of the total linear trend – the envelope (two lines, red and black, Fig. 7.2) of the SAG periods of force growth over 16 cycles. On each section of one cycle of displacement Δhi there is a constant increase of the force on the indenter $\Delta F_i = 250, N$. Each new step of the cycle of active increase of the force ΔF on the diagram is approximately linear (a-b-c). This is the process of elastic-plastic displacement of the indenter on the active section of increase of the force and displacement. It is clearly seen that the increase of the force on each new cycle can be represented in two stages Fig.10/3: Δhi= Δh1+Δh2. Δh1– mixed, elastic-plastic. Δh2 – plastic stage. During the entire active cycle Δhi there is a general increase of the elastic-plastic and plastic components. The slope of the linear trend of the section a-b-c depends on several parameters of the MKI process, which in turn determine the value of each component of the total indentation power, all components are shown in (2.2).

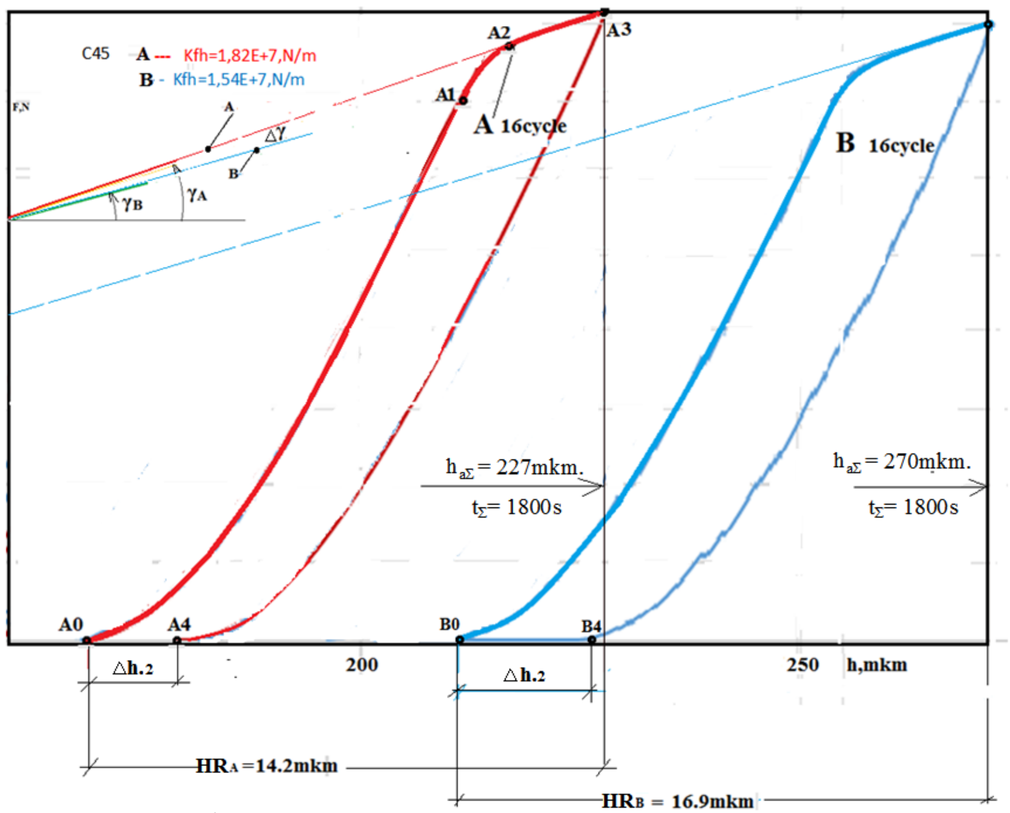
During the period of the force pause of indentation SYNCYCL (reverse), in the CYMKI method, the activated volume of the material remains in the stressed deformed state, which was created earlier by the force F(h) acting on the material. Let us designate the period in the absence of the pressure force SYNCYCL (Fig. 11b trajectory A3-A4) as Rhi = RHi - Δh2i, mkm. During this period, the rheological process of relaxation of the energy of the stress and strain field occurs, irreversible structural transformations of the activated volume Va occur. We characterize this rheological process by the specific rheological power PHt, see (2.2). The power PHt is a part of the main component of the power of the MK process PHIx(h). As a result of summing the power of different processes, the level of the total physical power (hardness) of the material PHIx(h) decreases, the empirical hardness index decreases accordingly. For this reason, the slope of the linear trend in the Fcycle (h) diagram, variant B, decreases relative to variant A. As a result, the generalized velocity parameter kfh decreased Fig. 11b,c. The value of the hardness index PHI is affected by the duration of the unloading period Rhi SYNCYCL (the length of the pause section), during which relaxation of residual stresses in the activated volume, arising from the previous loading cycle, occurs. The duration of the SYNCYCL stage affects the total specific power of the MKI process (physical hardness). As a result, the slope of the linear trend of the kfh diagram changes. The work of irreversible changes in the structure (such as aging, metal tempering, etc.) is performed during the time period SYNCYCL of the reload. The longer the reload period, the greater the work of irreversible processes due to the relaxation of residual compressive stresses arising from the previous cycle. Thus, PHt is the latent power of the CYMKI process, it reduces the main active power of the mechanical work of the indenter. Therefore, the slope of the linear trend Fcycle(h) decreases, i.e. the generalized speed kfh decreases. The period SYNCYCL, in the CYMKI method, is the regulator of the value of the total generalized power of the MKI cycle process.

Fig. 11b shows the change in the value of the full amplitude of the indenter movement HR (the full amplitude is the total movement of the indenter over the period SAG of the active force increment ΔFi and the time SYNCYCL). In this case, we have HRB > HRA , the difference in these parameters determines the change in the slope of the trend $\Delta k_{fh}(h,H) \propto \Delta tg(\gamma)$ of the entire diagram, Fig. 11c. The difference in HR causes a change (shift) in the contact line at the conjugation of the surface and the indenter sphere and the imprint of the previous cycle.

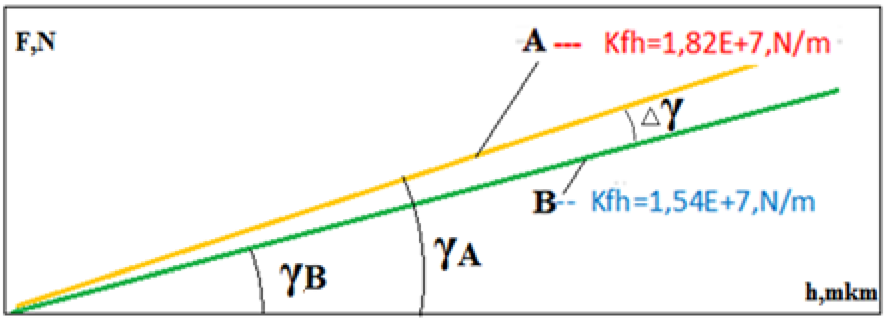
Fig. 11d shows a conventional point K on the contact line of two surfaces. This is the conjugation line of the surface formed by the previous cycle and the indenter sphere in the new cycle. In variants A and B, an activated volume with different densities of dissipated energy of the displaced material over the same period of time Δti is formed. As a result, we can set different constant specific power of shape change (constant physical and empirical hardness), characteristic of a given material and specified indentation parameters.


C45
A --- Kfh=1,82E+7,N/m
B -- Kfh=1,54E+7,N/m
A2
A3
B2
A1
B1
A 16cycle
B 16cycle
A0
A4
h,mkm
200
250
Δh1A
14.2mkm
Δh1B
16.9mkm
1cycle A
1 cycle B
hAmaxΣ = 227mkm
hBmaxΣ = 270mkm

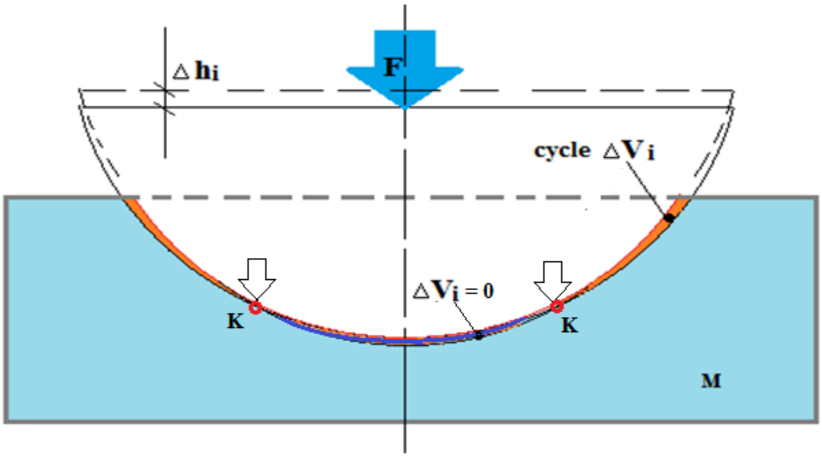
a.


C45
A --- Kfh=1,82E+7,N/m
B - Kfh=1,54E+7,N/m
A2
A3
A1
A 16cycle
B 16cycle
Δγ
γB
γA
haΣ = 227mkm.
tΣ= 1800s
haΣ = 270mkm.
tΣ= 1800s
A0
A4
B0
B4
200
250
h,mkm
Δh.2
Δh.2
HRA =14.2mkm
HRB = 16.9mkm

b.



c.



d.

Fig.11 Comparative analysis of the MKI process parameters in the last cycle (16) for two CYMKI variants A, B:

a. Fragments of two cyclic diagrams A, B. in the last cycles are combined on one axis. The difference in the accumulated total displacements is shown: A - $h_{a\Sigma}$ = 227mkm B - $h_{a\Sigma}$ = 270mkm. Different slope of the trend line for each complete diagram.

b. Comparison of the 16th cycle of the CYMKI diagram in two variants A, B. For the ΔFi 16 cycle of each variant, a linear trend $k_{fh}(h,H) \propto tg(\gamma)$ is shown in the active phase of force growth. Δγ is the growth of the trend slope angle (respectively, the growth of Δ_{kfh}).

c. An example of processing the data of the values γ_A γ_B . The change in the generalized velocity k_{fh} MKI by the value Δ_{kfh} (Δγ) is shown. In variant B, the slope of the linear trend has changed. This is the result of the growth of HR (the difference in SYNCYCL) in these diagrams: HRB > HRA.

d. The point K is shown conditionally at the intersection of the contact line of two surfaces. This is the line of conjugation of the surface formed by the previous cycle and the body of the indenter sphere in the new cycle.

When changing the value of the displacement HR, mm (the full amplitude of the indenter displacement per cycle), while maintaining the time for HR, the displacement causes a change (an increase or decrease) in the rheological velocity in the active section of the cycle υ_{Rh} = $\Delta h_i / \Delta t_i$, m/s. As a result, the main parameter k_{fh} will change, and the hardness of the material will change proportionally. Thus, by purposefully changing the physical conditions of the hardness measurement process, we can set the desired physical measure of hardness (set the required specific power of dissipated energy). By maintaining certain main parameters of CYMKI, when testing different materials, we will obtain the corresponding correct hardness scale characteristic for certain process parameters in this method. In this way, we will provide similar hardness measurements for a certain constant physical unit of hardness measurement. In the case considered above, testing based on CYMKI - ISP NANU [14,19] models the principle of empirical testing of the material hardness number. The authors of the method searched for process parameters under the previously established empirical parameter (number) of hardness, repeating the formal value of hardness, recognized utilitarianly as the Brinell scale.

Conclusion.

The generalized rate of force growth $k_{fh}(h,H)$ in variant A $k_{fh}(h,H) = 1{,}84E+7, N/m$ is greater than in variant B, $k_{fh} = 1{,}54E+7, N/m$ Accordingly, the physical and empirical hardness in variant A is greater than in B.

The indenter displacement Δha1cycl in the active period SAG of force growth are respectively inversely related:

$$B\ \Delta ha_{1cycl} = 17{,}3 \cdot 10^{-6} m > A\ \Delta ha_{1cycl} = 14{,}5 \cdot 10^{-6} m\ .$$

From the comparative analysis and the results of calculations by the physical method of diagram analysis, it follows that the hardness according to the Brinell scale can be obtained using simple direct measurements of the total parameters of the CYMKI diagram. For this, we determine the macro parameters haΣ, hpΣ , the average value of ΔFi, for the entire diagram of the cyclic process $F_{cycle}(h)$ Fig. 8, 9 . In this case, each MKI cycle can be considered as a separate act of material hardness testing. In general, we obtain the average statistical parameter of the generalized rate and, accordingly, the average value of the material hardness for 15 test cycles (the first cycle is relaxation). If the material or process is non-uniform or anisotropic in depth, then the hardness index will be different in depth, etc., we will receive a correspondingly different index k_{fh} (deviation from the linear trend) and see a different hardness value.

4. *Generalized indentation rate is a universal integral criterion of hardness in CYMKI. Physical measure is an algorithm, a unit of measurement, a hardness scale, generalized MKI rate, a parameter of the linear trend of the function F(h).*

From the analysis of the CYMKI diagrams it follows that by adjusting the values of physical parameters during testing, it is possible to model (create) different specific power of the PHI(h) MKI process, i.e. it is possible to change the slope of the linear trend $k_{fh}(h,H)$, therefore it is possible to change the generalized cyclic MKI rate $k_{fh} = F_{i\Sigma}cycle/\Delta h_{i\Sigma}cycle$.

By changing the parameters of the CYMKI process, it is possible to purposefully change the hardness measure, the physical unit, the standard of material hardness, and, accordingly, it is possible to create a new scale of hardness of sphere indentation in a cyclic process. The degree of physical correctness and other characteristics for the new scale will be discussed further.

Fig. 11 shows the elements of the F(h) function diagram for one cycle. The ratio of the parameters of elastic-plastic and plastic displacements in the section Δh, the value of the rheological velocity of displacement $\upsilon_{Rh}(h,t)$, the rheological rate of force growth $\upsilon_{Rf}(h,t)$ and the value of displacement HR determine the resulting generalized rate of indentation force growth kfhi = ΔFai/Δhai = const. By mechanically selecting (iterating) the ratio of these parameters, the testing machine automatically maintains the mode of constant parameter kfhi. The period of reaching the mode of constant value of the generalized rate of force growth is visible in the diagram as a nonlinear section – relaxation of the process in Fig. 9 it proceeds to the point ho. After this point, the cyclic process gradually reaches the mode of constant rate of force growth, and constant generalized rate of cyclic MKI $k_{fh} = F_{i\Sigma}cycle/\Delta h_{i\Sigma}cycle$.

It is clearly seen in Fig. 7.3 how the rheological rate of force growth changes in the section a-b (Δh1) of the active phase of each cycle, it gradually increases (acceleration), therefore, strictly speaking, the generalized rate of force growth in the cycle kfti const . The ratio of the parameters Δh1 and Δh2, within the entire active phase of the cycle Δh (Fig. 7.3), can regulate the value of kfti. This is possible due to the choice of the pause duration SYNCYCL .

Thus, when searching for the required mode, indentation parameters CYCLE, it is possible to achieve the average value of speed in the cycle $\bar{k}_{fhi}$ = const required for a given material. By maintaining the speed standard $\upsilon_{Rh}(h,t) = const,$, the unit of hardness measurement is maintained, i.e. the hardness scale is maintained. In this case, we will obtain a linear trend $\bar{k}_{fh}$ for the entire CYCLE KI diagram, and accordingly we find the hardness value itself, for example, on the Brinell scale. If we apply arbitrary constant main physical parameters of the full MKI cycle in MKI, when testing different materials, we will obtain an arbitrary, but at the same time physically correct hardness scale, with some new value of the specific power standard MKI, there will be a new measure of hardness J/m3. We previously called such a hypothetical scale segmental, relative to the first MCJ scale. An example of constructing a new scale, choosing a new measure of hardness, is the CYCLE KI diagram - B variant, Fig. 6.

From comparison of diagrams A and B it follows that in diagram A the generalized velocity kfh is higher than in variant B. From the formula for calculating k_{fh}A (10.9) it follows that this is caused by the fact that in variant A the rheological component of the force increase rate is higher than in variant B: $k_{fRA} > k_{fRB}$, it is in the numerator, while the denominator is constant $k_{hRA} = k_{hRB}$ = const. At the same time, in two variants the same indenter movement velocity $\upsilon_{hi}(h,t)$ = $h' = x' = \partial h/\partial t = const$, m/s, (10.8) , it is in the denominator. As a result, the force increase rate of variant A is higher than variant B: $k_{fhA} > k_{fhB}$. Based on the analysis of the experimental diagrams of KI ISP NANU, it was found that the hardness monotonically increases with increasing rheological velocity k_{fR}, all other parameters of the MKI sphere being equal. In particular, in similar tests A and B the same steel C45, but variant B has a lower rheological velocity kfR of force increase. This result became a direct confirmation of the formulas for calculating physical hardness and confirmed the conclusion about the influence of the rheological component in the total specific indentation power (Part 2.1, formula 2.6).

5. *Examples of calculating the hardness of steel in HBW units according to CYMKI diagrams, indenter sphere D 2.5 and 0.76 mm.*

Let us use the experimental diagrams in Fig. 12a, constructed as a result of testing the hardness of steels according to the Brinell scale. The method is based on the correlation analysis of the parameters of the cyclic diagram F_{cycle} (h) CYMKI ISP NASU, published [14,19]. Let us apply the formula of the physical theory of hardness (6) to the analysis of the F_{cycle} (h) diagrams and calculate the material hardness according to the Brinell scale HBW using a physical method. Fig. 12a shows the linear trend of the cyclic diagram MKI for four steels; the dependence for each linear trend is shown: $Y=k_{fh}*h$, where Y=F, N, $h=h_{a\Sigma}$, k_{fh} is the physical parameter of the generalized speed (dimension N/m). The parameter kfh is equal to the value of the linear trend, constructed as a common straight line on the diagram, which connects all sections with an equal speed of active growth of force ΔFcycle (h). An example of a complete diagram of steel C45, Fig. 9a. Fig. 12, the following steels were tested: 45, 15Х2НМФА, 08ХГМНТА, 10ХМФТ. The formula for calculating the hardness HBW on the Brinell scale is the formula from (6):

$$HBW = k_{fh}/\delta\pi R \qquad (16)$$

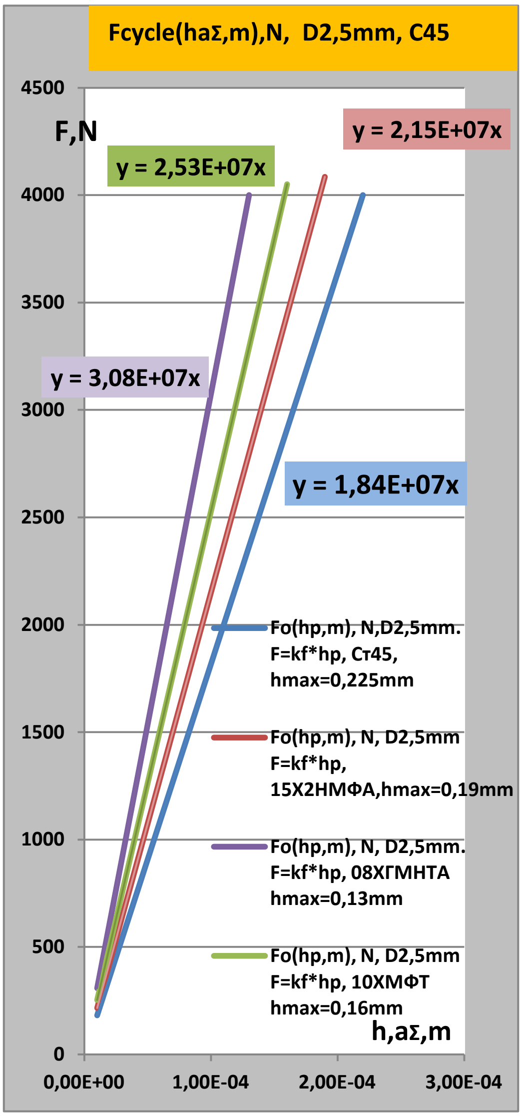
By simple transformations (16), we obtain the formula for calculating the value of the shape parameter δ of the contact physical surface of the MKI process by a sphere:

$$\delta = \pi R*HBW/kfh \ (16.1)$$

By substituting the experimental value of kfh and the hardness value of the HBW standard tested in the experiment into formula (16.1), we obtain the refined parameter δ=2.54. It is advisable to use this value in calculations using the CYMKI ISP NASU sphere D2.5mm test method for materials of different hardness.

The result of the theoretical calculation of the hardness of steels Table 4, in Brinell scale units, the calculated parameters are determined from the CYMKI ISP NASU sphere D2.5mm diagrams, Fig. 12a, calculation formula (6). Fig. 12b shows the results of the calculation and construction of the $A(V_{o\Sigma})$J diagram, from which the value of PHM, J/m3 - physical potential macrohardness of these steels was obtained, the diagram parameters were obtained from the results of analytical processing of the linear trend equations $F_{cycle}(h_{a\Sigma})$, formula (9.1.1), $V_{o\Sigma} = Vo(h_{a\Sigma})$. The theoretical calculation of hardness in steel in HBW units by the physical method based on the CYMKI ISP NASU force diagram coincides with the results of hardness testing of these steels obtained by the correlation empirical method, the results are published in the article [14,19]. Table 4 shows the calculation results and data for comparison.

The performed calculations and theoretical studies of the PHM property showed a stable relationship between this parameter and the parameter $k_{fh}(h, H)$ and value of the material hardness. These results open up a more effective method for assessing the hardness of a material, both by physical and empirical methods. At the same time, I developed similar methods for the analytical physical analysis of uniaxial tensile material (UTM) diagrams, for which the PHMUTM potential function was obtained. Thus, based on a unified physical approach, the foundations of a universal criterion have been developed, and functions of the state of the process of changing the shape of a solid are proposed. This approach can be used to assess the physical universal parameters of the state and to assess the standard characteristics and parameters of the (empirical) properties of a material. In Part 2.9, examples of analysis of the properties of the function PHM=∂A/∂V are considered.



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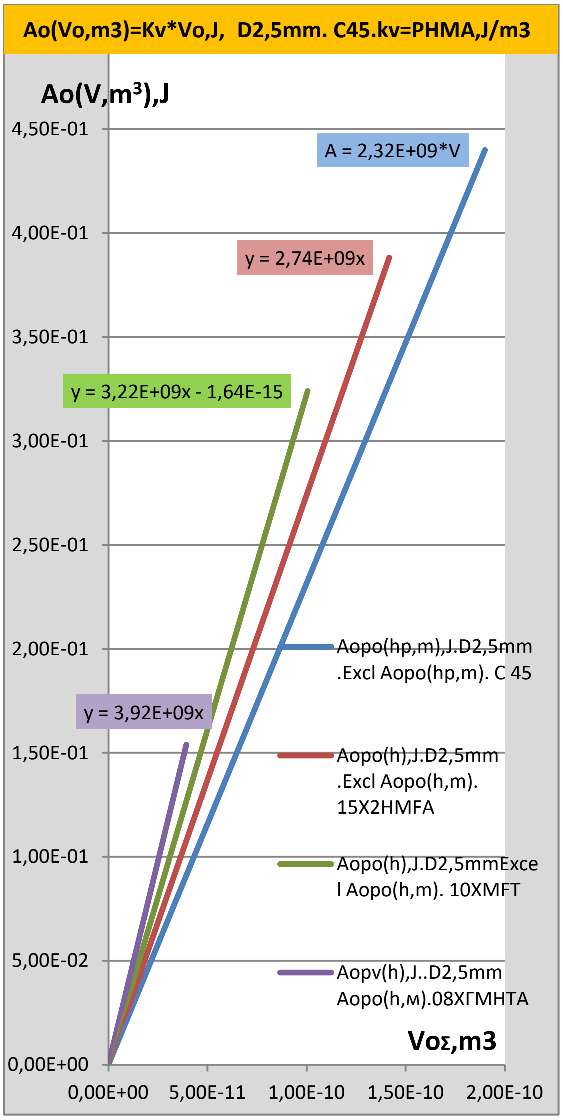

b

Fig. 12. Experimental diagrams of CYMKI ISP NASU [14]: a. $F_{cycle}(h_{a\Sigma})$, $h_{a\Sigma}$ is the value of the total accumulated depth of elastic-plastic displacement of the sphere indenter, material steel 45, 15X2HMFA, 08XГMHTA, 10XMFT, the diagram is constructed based on the parameters of the diagram of the correlation method for measuring Brinell hardness, D2.5mm [14]; b. Graphs of the thermomechanical potential $A_o(V_{a\Sigma})$ function, obtained based on processing the data from the diagrams of Fig. 12a, $V_{a\Sigma}$ ($h_{a\Sigma}$) is the total cyclically accumulated activated volume, discussion in P2.7.

Let us consider a new example of applying the physical method of analyzing the CYMKI diagram and formula (6) to calculate the hardness number. In Fig. 13a CYMKI diagrams of four steels S30408, 18MnMoNbR, SA508-3, Q345R, published in [20]. In the article [20] some data on the main physical parameters of the CYMKI process required by us were missing. The calculation of the hardness number of steels according to the Brinell scale was performed under the assumption that the main process parameters not shown in these tests repeat the conditions of CYMKI ISP NASU (more details on the parameters in the previous calculation). In this testing method, a new range of maximum indentation depth was used: in CYMKI ISP NASU it was haΣ = 0.227 mm, now we have $h_{a\Sigma}$ = 0.13 mm; at the same time, the sphere diameter D2.5 → D0.76 mm decreased.

Таблица 4. Результат теоретического расчета твердости сталей, выполнен по диаграммам CYMKI ISP NASU сфера D2,5mm [15], формула физического теоретического метода (6).

Steel grade	State Standard 9012-59 BH, HBW $\times 10^7, Pa$	Proven method ISP NASU $\times 10^7, Pa$	Physical potential macrohardness PHM $\times 10^7, Pa$	choreic - rheological coefficient k_{CHR}	Correct Physical potential macrohardness PHMC= $k_{CHR} \times PHM$ $\times 10^7, Pa$	$k_{fh} = \Delta F / \Delta h$ $N/m \times 10^5$
1	2	3	4	5	6	7
08ХГМНТА	306	301	392	0,8	314	308
10XMFT	255	254	322	0,8	258	253
15X2HMFA	222	223	274	0,8	219	215
45	183,7	189	232	0,8	185,6	184

When switching to a sphere diameter of 0.76 mm and a smaller range of MKI depth, we obtain a different scale of hardness measurement (a new measure of hardness). In this case, we did not fulfill the physical conditions of similarity of material testing that were used for calculations according to the diagrams in Fig. 12a. In this case, according to the theory, it is necessary to make an adjustment - a transition to a different measure of hardness, which occurs with new MKI parameters (changed d sphere, etc.). The methods and principles of adjustment were discussed in more detail earlier, separately considered in [3, 4].

For analytical calculation of changes in the scale of the hardness scale (change in the measure of hardness, taking into account the change in the main parameters of the KI process), to determine the hardness in one unit established by the standard, I developed a physical analytical method for adjusting the hardness number obtained with deviations in the dimensions of the sphere and the range from the standard (conditions of previous tests). In our case, there was a decrease in the diameter of the sphere and a decrease in the depth h_{max} (h_{cycle}). A separate article will be devoted to this adjustment method in detail. In particular, we will now consider an example of the results of an analytical solution to such a problem for testing the hardness of steels according to the diagram in Fig. 13a, from the article [20].

Using the analytical theoretical method of adjusting the physical parameters of the KI process when testing the material hardness under different conditions (different scales), the similarity coefficient K_{fx} = 2.5 was determined, which allowed us to obtain the material hardness value in Brinell scale units. The adjustment method takes into account the change in the main physical parameters of the CYMKI KI process, relative to the established standard or main method. In particular, testing at D0.76 mm Δh = 0.095 mm, was translated using the similarity coefficient into physical parameters for KI D2.5 mm, Δh = 0.13-0.21 mm (see the first calculation of CYMKI ISP NANU).

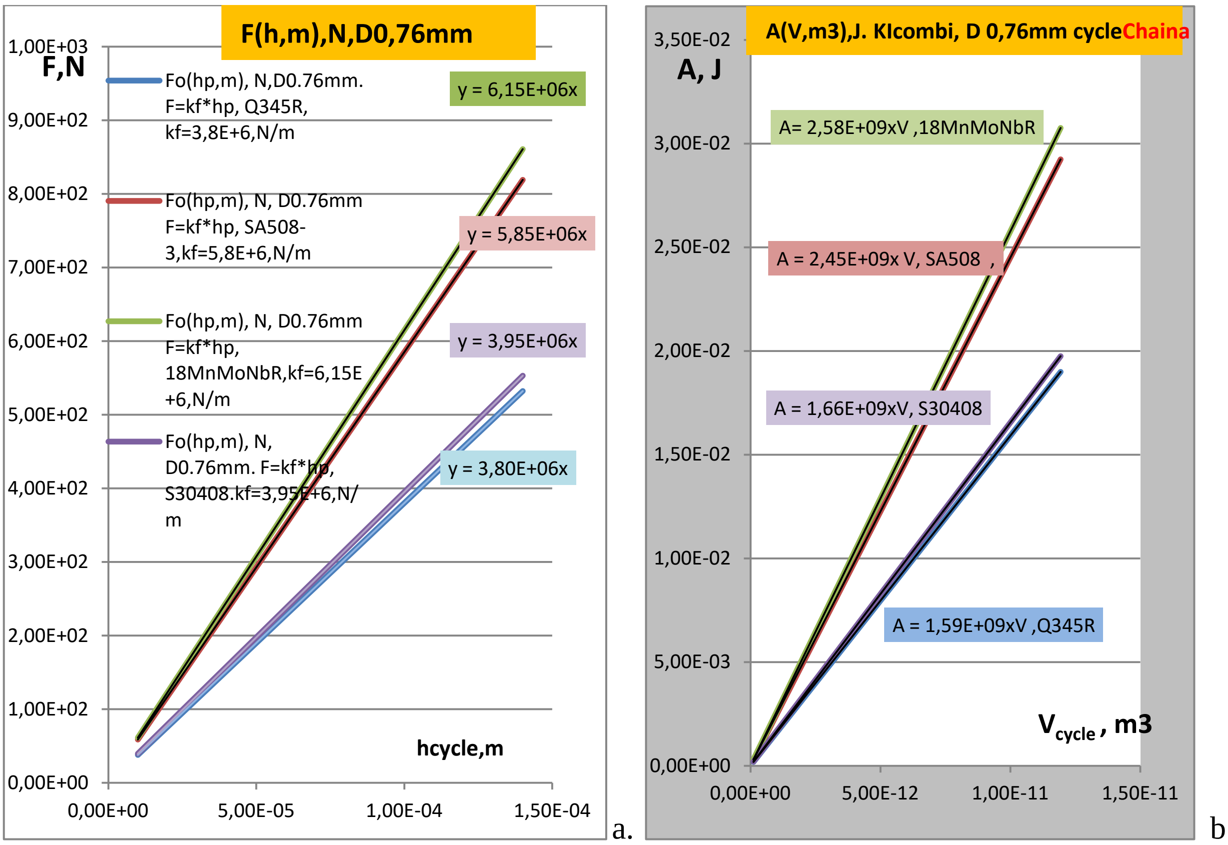

Fig.13 a) Experimental diagrams of CYMKI steels S30408, 18MnMoNbR, SA508-3, Q345R, published [20]. For P. 2.7, in diagram b the activated volume Vcycle is an independent variable, Excel method, punctual.

The results of calculating the hardness of steels using formula (6) are shown in Table 5. The similarity coefficient K_{fx}=2.5 (column 5) takes into account the change in the main physical parameters and conditions of the KI process. The calculation result showed that for the case of a small diameter D0.76 mm, the physical potential of hardness PHM and the value of empirical hardness PHI_{xk} are approximately equal $PHI_{xk} \approx PHM$. In the case of CYMKI ISP NANU D2.5 mm, see above, there was a discrepancy Table 4. This discrepancy is presumably caused by the transition from the KI macro range process to the micro range. In the case of D=0.76mm, the value of the shape change parameter Xsv increased approximately twofold.

Table 5. The authors of the diagrams in [20] did not show data on the hardness of the tested steels in Brinell units; I was unable to find any in open sources of information. Readers will make this comparison on their own. The results of approximate calculations that I obtained can be considered as a demonstration of the capabilities of the new physical method for analyzing cyclic diagrams. In this case, it was important to obtain the same order of magnitude of the hardness number, check the algorithm of the method, and compare the order of magnitude of the hardness, the proportions of these values, for the tested steels, using other sources for this. Empirical formulas for the relationship between the tensile strength (obtained in the article) and the HBW hardness were used as a criterion for an approximate estimate of the hardness of steels in Fig. 13a; the calculations showed satisfactory agreement between the theoretical and empirical values.

Table 5. The result of the theoretical calculation of the hardness of steels using the CYMKI diagrams, sphere D0.76 mm, Fig. 13a, data [20], hardness calculation formula (6).

Steel grade, alloy	State Standard HBW, Pa	$k_{fcycl} = \frac{\partial F}{\partial h_{cyc}}$ N/m	$\alpha = \frac{1}{\delta \pi R}, 1/m$ $\delta = 2{,}5$ R=0,38mm D=0.76mm	$PHI_{xk} = \alpha \cdot k_{fcycl} \cdot k_{fx}$, $J/m^3 = N/m^2$ Kfx=2,5	Δ %	Physical potential macrohardness PHM $J/m^3 = N/m^2 = Pa$	choreic - coefficient k_{CHR} (Δh,мm)	PHMC =HBW $k_{CHR} \times PHN$ J/m^3 Pa
1	2	3	4	5	6	7	8	9
S30408	**N/A**	$0{,}395 \times 10^7$	164	160×10^7		166×10^7	1.0 (130)	166×10^7
18MnMo NbR	N/A	$0{,}615 \times 10^7$	164	252×10^7		258×10^7	1.0 (130)	258×10^7
SA508-3	N/A	$0{,}585 \times 10^7$	164	240×10^7		245×10^7	1.0 (130)	245×10^7
Q345R	N/A	$0{,}380 \times 10^7$	164	155×10^7		159×10^7	1.0 (130)	159×10^7

6. Discussion. Conclusions.

From the analysis of the cyclic diagrams of MKI with a sphere D 2.5 mm (ISP NASU) it follows that in the active phase section of each cycle the constant reference speed of the indenter movement $\upsilon_{hi}(h,t) = \partial h / \partial t = const,\ m/s$ ..

To maintain a constant scale of the hardness scale, a constant unit of hardness in MKI, when testing materials of different hardness - a constant generalized speed MKI is required. In this case, with MK $k_{fh}(h,H) = const$ I, the physical condition of similarity of indentation is met, a correct physical scale of hardness is formed, and the physical unit of measurement of hardness is preserved along the entire scale.

The generalized speed of indentation $k_{fh}(h,H) = const$ is a universal integral criterion of hardness in CYMKI, which allows for a correct analytical transition to the established measure (unit) of hardness of materials and the corresponding correct scale of hardness.

Changing the absolute value constant of the generalized speed MKI $k_{fh}(h,H) = const$ set in some method (for example MCJ, CYMKI) leads to a deviation from the standard of the hardness measurement unit and makes the measurement results and scale incorrect.

The rheological speed of indenter movement $\upsilon_{Rhcycle}$ - at the active stage of MKI in the CYMKI method - ISP NASU and in the MCJ method are approximately equal, Table 3:

$$\upsilon_{Rhcycle}(h,t) \approx \overline{\upsilon}_{RhMCJ} = \text{1-2 mkm/sec}, \ .$$

The value of the rheological rate of indentation force growth in the CYMKI - ISP NASU method for C45 steel and in the MKI tests of MCJ steel (their grade is not exactly known) are practically the same Table 3:

$$\upsilon_{Rf} = \Delta F_i / \Delta t_i,\ N/s = \text{25-26, N/sec}$$

Table 3 shows the results of steel hardness calculation performed by the physical method, according to the published MCJ data [14] (their steel grade is not exactly known).

An analysis was made of the influence of the property of the function type and the value of the derivatives $F'_h = k_{fh}(h)$ obtained for the F(h) functions of different nature, under different conditions of the MKI processes. For the physical analysis of the F(h) diagram, the generalized velocity k_{fh}(HB, V, S, t, T), where T is the temperature of the activated volume, is conveniently represented as a function of the sum of several process velocity components. A detailed analysis of the influence of the generalized velocity components on the function and hardness number MKI showed that the generalized velocity can be considered as the sum of three components (17) of the conditional generalized velocities of change of force KI. As a result of the research, it was established that the value of $k_{fh} = F'_h(h) = dF/dh$ is the sum of three main components, their combined effect can be represented by formula (17):

$$k_{fh}(h, HB) = \mathbf{k_{ch}}(h,V) + \mathbf{k_t}(t) + \mathbf{k_{ses}}(T, SES), \; N/m \quad (17)$$

Where, k_{fh} is the parameter of the linear trend of the generalized growth rate F(h) of MKI;

k_{ch}(h,V) is the choric parameter that takes into account the contribution to the rate kfh of the continuous process of changes in the shape-changing function Xsv(h). It depends on the depth h, the activated volume -Va and the projection contact area of the indenter - Sap.

k_t(t) is the rheological component, it depends on the time (speed) of the process t of forming the activated volume to a given point hmax(t) and the rheological speed of the indenter υi=dh/dt;

$k_{ses(}$T,SES) is the root physical parameter of the generalized MKI rate of the material, it displays the contribution to the total rate k_{fh} of the structural-energy state (SES) and the temperature of the activated volume of the material.

Some parameters of the MKI process in the ISP NASU and MCJ methods.

S45 tiact =5-10sec single-act MKI, D2.5mm, υ_{Rhact} = 2 mkm/s. h_{iact} =10mkm

S45 $t_{\Sigma cycl}$ = 28min, CYMKI, D2,5mm, $\upsilon_{Rhcycle}$ =1-2 mkm/s, ha_{Σ} =227 m km

MCJ t_{MCJ} = 30min = const, $\overline{\upsilon}_{RhMCJ} = \frac{h_{MCJ}}{t_{MCJ}}$ = 1,81mkm/sec = const. h_{MCJ} = 3250mkm= const

In the CYCLE - ISP NASU MKI method, a certain shape of the tool was used - a D2.5mm sphere indenter, an original way of controlling the physical parameters of the process inside the cycle, to create a certain (specified) average specific active power of MKI for a full cycle. As a result of orthogonal pressing of the sphere indenter into the material, an individual process of activating a certain physical volume of material (Va $\approx$Vph) and a specified constant parameter of forming Xsv was created. The main, unambiguous physical and mechanical characteristic of the material property in the MKI process is physical hardness, specific power of forming. In this method, the hardness depends on the ratio of rheological velocities . Where, and from the formulas $k_{fhcycle} = \frac{\upsilon_{Rf}(h,t)}{\upsilon_{Rh}(h,t)}$. Где, $\upsilon_{Rh}(h,t)$ и $\upsilon_{Rf}(h,t)$ Part 2.3 (9.10), (9.11). In the CYCLE method, the indenter shape parameter $\alpha_{PHI} = \frac{1}{\delta\pi R}$ (6.2) is taken into account. For the CYCLE MKI method to correspond to the Brinell MKI method and scale of empirical hardness (macrosphere indenter, single-stage process, imprint is measured), it is necessary that the average rheological velocity of the indenter translational movement in the SAG phase $\upsilon_{i\,cycle}$ of the process be equal to: $\upsilon_{Rh} = \bar{\upsilon}_{it.CJ} = 1{,}8 \cdot 10^{-6}\, m/sec$, where, $\bar{\upsilon}_{it.CJ}$ is the average velocity of the indenter movement adopted in the fundamental MCJ method.

$$\upsilon_{Rh} = \upsilon_{i\,cycle}(h,t) \approx \bar{\upsilon}_{it.CJ} = \partial h/\partial t \approx \frac{h_{CJmax}}{t_{MKJ}} = 1{,}8 \cdot 10^{-6}\, m/sec = const$$

The selection of the necessary mechanical parameters of the CYCLE KI process is carried out by the testing machine control program, the period duration (SYNCYCL, HR, Δh1, Δh2) is selected by the method of successive approximations, and the desired speed $\upsilon_{Rh}(h,t)$ is obtained as a result.

As a result of modeling (selection of parameters) of physical conditions during CYCLE MKI, the following condition is met:

$$\upsilon_{Rh} = \upsilon_{icycle} \approx \upsilon_{iMCJ} = (1 \div 2) \cdot 10^{-6}, m/s$$

As a result of these actions, we obtain the required slope (linear trend) of the diagram during testing (the same as the generalized speed), $k_{fhcycle}$ it is approximately equal to the slope of the reference root diagram of testing a material with the same hardness value in the MCJ method. These targeted actions in CYCLE MKI achieve a repetition of the principle of constructing a hardness scale and indirectly (with an accuracy of up to a constant factor) preserves the scale of the primary correct physical hardness scale Calverta Johnson.

Some of the key physical principles of the MCJ scale formation have been lost over many years without systemic transformations of hardness measurement methods, only some initial principles have been preserved, approximate values of some main parameters are also used, etc. In empirical standard methods, there is no control over the constancy of the main parameters Va (h), Xsv, when changing the indenter type, the depth hmax is not constant in the act of measuring the MKI indentation and calculating the hardness number, etc.

Conclusions.

Research has shown that when changing the size, shape of the indenter, MKI process parameters, to determine the Brinell hardness number, in CYMKI IPS NASU it is necessary to perform new complex tests, carry out an intuitive selection of new correlation parameters, etc.

A new physical analysis method can significantly simplify the testing technology, some technological requirements are reduced, it is analytically easy to switch to the analysis of CYMKI data for spheres of different diameters, it is possible to determine the hardness according to another standard and arbitrary scale. The physical method of analysis CYMKI was tested on the data obtained in MKI by spheres of different diameters, it showed a satisfactory result

The authors of the works CYMKI - ISP NASU see the parameter kfh as a trivial tangent of the slope of the diagram F(h), do not consider the physical properties of the KI process, the relationship between the diameter D of the indenter and the main parameters of the function F(h) during its approximation is not determined.

At the same time, the quantitative results (hardness number) and the experimental-analytical diagram of the correlation methods of ISP NASU made it possible to confirm the calculations of hardness, performed by the formulas of physical theory, experimentally confirmed the theoretical foundations of the physical method.

If the macro parameters of the test are kept constant during cyclic MKI of materials with different hardness: tΣ, hΣ, VΣ, $\upsilon_{hi}(h,t)$, tΣ, we obtain a physically correct hardness scale, in a particular case (i.e. specific parameter values), we find the hardness number on the Brinell scale. An example of changing the scale scale is considered above in diagrams A, B. The initial root reference parameters of MKI, for the correct measurement of the hardness number in one units, were established in the root measurement method of Kelvert and Johnson. In the standard method of Brinell et al., some of the physical requirements for the similarity of processes during testing are not approved and are not met, therefore we obtain a size effect, etc.

The method of instrumental kinetic cyclic indentation with a sphere allows modeling the conditions for ensuring a given value of the generalized indentation rate $k_{fh} = F_{i\Sigma}\text{cycle}/\Delta h_{i\Sigma}\text{cycle}$. The value of this rate is directly proportional to the specific power of the MKI process of the material (the root of the value of the physical hardness number of the material). This property was confirmed theoretically by analyzing the results of hardness calculation using the experimental data of the CYMKI ISP NASU method and the test data using the MCJ method (see Section 2.5). The value k_{fh} depends on the ratio of the rheological rate of force increase and the rheological rate of indenter displacement increase. The required value k_{fh} in ISP NASU tests is obtained by iteration (targeted selection) of the ratio of the main parameters of the MKI process: ΔF_i, Δh_i, **HR**, Δt_i. Analysis of the CYMKI sphere indentation process showed that this method can create a physical process of changing the shape of the activated volume with a specific generalized power MKI (physical hardness) similar to the indentation process created by a conical indenter in MCJ. With cyclic macro indentation with an ISP NASU sphere, we simulate a reference process of hardness measurement with a certain specific generalized power, which corresponds to the hardness of a given material in recognized units of measurement or in a certain empirical hardness scale. The first standard of the MKI process was created in the root method of indentation by a truncated cone MCJ. The first correct scale of numbers and method of measuring hardness for different materials were created. This scale and method became the basis on which various empirical methods of measuring hardness were then intuitively developed, with violations of some principles.

By means of CYMKI parameter variations, it is possible to select the required value of the measure or unit of hardness (meter of specific power MKI) for forming a given or new independent (segment) scale. Thus, CYMKI allows to simulate-repeat with some accuracy the desired MKI process, which was performed by an indenter of different shape in a different macro range. With the exception of the process with a sharp indenter. To simulate (similarity) the process by the CYMKI method, it is necessary to initially calculate the required physical parameters of these processes and repeat them in subsequent CYMKI tests. The CYMKI method and technology allows to form an arbitrary independent physically correct scale of material hardness (a new measure of hardness), but for this purpose a new algorithm of the CYMKI process should be initially analytically formed, i.e. to approve the main parameters for MKI, to assign a standard unit of hardness, but at the same time, the main physical principles of MCJ should be preserved. Otherwise, it is necessary to introduce a new correct hardness scale, etc. If these principles are violated, then MKI causes a size effect, etc. uncontrolled deviations in hardness values.

CYMKI is a universal method for testing material hardness, allowing you to simulate (set) different parameters of the indentation process (simulates a change in the indenter size and KI range). In this case, you can repeat the basic principles, scale and unit of hardness measurement created in the fundamental MCJ method. In Part 2.4, the principles and physical main parameters (constants) of MCJ were considered. The results of the studies made it possible to formulate an algorithm and rules for the CYMKI process.

The studies showed that the physical method of analyzing CYMKI data made it possible to find the hardness value in a universal physical unit, general formulas were obtained that allow you to correctly and easily find the material hardness number for different indenter sizes, an algorithm and a program (a simple version) for analyzing F(h) cycle diagrams were created.