IMPROVEMENT OF A PROCEDURE FOR DETERMINING THE BRINELL HARDNESS OF STRUCTURAL STEELS BASED ON THE RESULTS OF INSTRUMENTED INDENTATION

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Using the created experimental equipment for testing metals by the method of instrumented indentation, a procedure for determining Brinell hardness during the nondestructive testing of structural elements has been developed. In contrast to the conventional method, the hardness is determined by the proposed procedure using the proportionality parameter of plastic indentation, a, which is equal to the slope of the instrumented indentation diagram in the coordinates maximum force of cycle F_{max} – residual indentation depth h_p after removing the test load of this cycle. Based on the results of a series of tests by the method of instrumented indentation of hardness standards, a linear correlation dependence was obtained between the Brinell hardness value and the proportionality parameter of plastic indentation in a wide range of measured hardness values of 110–650 HBW. The peculiarities of using this procedure and its limitations are analyzed on a number of structural carbon, heat-resistant, and high-strength steels. It is shown that the Brinell hardness measurement results, obtained by the improved procedure, agree within the permissible error with the results of the conventional DSTU ISO 6506-1:2019 method. The difference between their values does not exceed 3.9%. The presented improved procedure can be used in the laboratories of research and educational institutes, central factory laboratories and specialized divisions of various subordination, and other organizations involved in monitoring the condition of the operating critical equipment and setting its further service life both in the laboratory and in the field.

Keywords: Brinell hardness, instrumented indentation method, indentation diagram, portable tester, procedure.

Introduction. In the world practice, considerable attention is paid to the improvement of nondestructive methods for monitoring the state of the metal of critical equipment during operation. The recording of the indentation diagram in the force–indentation depth coordinates (the method of instrumented indentation) [1] during the nondestructive testing of the metal allows obtaining much more information about the state of the material compared to standard hardness tests. The instrumented indentation method has become widely used in determining various characteristics: Young's modulus, Poisson's ratio, hardening index, yield strength and ultimate strength, relative elongation and contraction ratio [2–7], creep characteristics [8, 9], in studying aging processes [10], determining the deformation curve under uniaxial tension [11, 12], studying residual stresses [13], determining mechanical characteristics under low-cycle loading [14], crack resistance characteristics [15, 16], and others.

The purpose of this work is to improve the procedure for determining the Brinell hardness of steels based on the results of instrumented indentation and to obtain new data for a number of structural, heat-resistant and high-strength steels on their hardness.

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1. Equipment and Research Methods. The Pisarenko Institute of Problems of Strength of the National Academy of Sciences of Ukraine conducted a set of studies on the development of equipment and a procedure for determining mechanical characteristics using instrumented indentation [17–20], including a procedure for determining Brinell hardness [21]. In contrast to the traditional measurement method, the hardness was determined by the proposed procedure using the proportionality parameter of plastic indentation a. This parameter is proportional to the slope γ of the indentation diagram in the coordinates maximum test load of cycle F_{max} – residual indentation depth h_p after removing the test load of this cycle (Fig. 1). With this approach, the determination of the Brinell hardness of metals does not depend on the elastic deformation of the measuring unit, the indentation depth, and the visual measurement of the diameters of impressions. It should be noted that establishing correlation dependences for certain groups of structural materials requires high material costs for specimen manufacturing and much time spent on hardness testing and indentation. In view of this, it is advisable to establish a single universal correlation dependence for determining Brinell hardness by the instrumented indentation method.
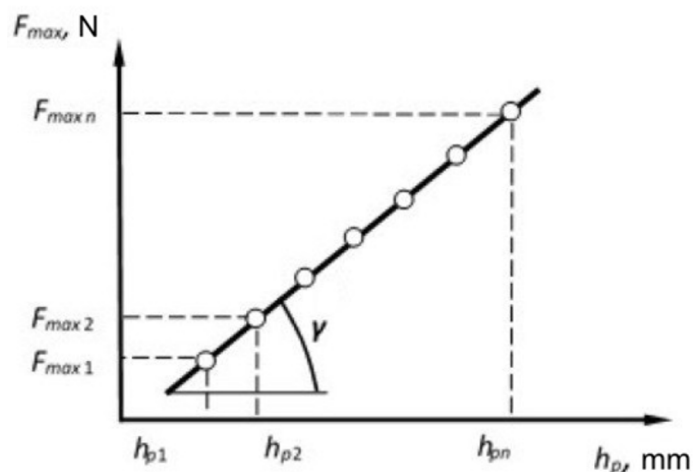

Fig. 1. Schematic diagram of instrumented indentation in the coordinates maximum test load of cycle F_{max} – residual indentation depth h_p after removing the test load of this cycle: F_{maxi} is the maximum test load of the ith cycle (N), h_{pi} is the residual indentation depth after removing the maximum test load F_{maxi} of the ith cycle (mm), and γ is the angle of inclination of the instrumented indentation diagram in the $F_{max} - h_p$ coordinates to the abscissa axis.

The essence of the procedure [21] was that the Brinell hardness was determined from the correlation dependence on the proportionality parameter of plastic indentation, a, determined from the cyclic indentation diagram in the $F_{max} - h_p$ coordinates:

$$HB = f(\alpha), \tag{1}$$

where $f(\alpha)$ is a function of the dependence of the Brinell hardness $HB,$ determined with a steel ball with a diameter of 2.5 mm according to the no longer valid GOST 9012-59, on the parameter a.

Based on the results of indentation tests and hardness measurements of the 15H2MFA, 15H2NMFA, 45, 08HGMNT, 10HMFT steels, a linear dependence was obtained for determining the Brinell hardness by the instrumented indentation method in a range of hardness values from 180 to 300 HB [21]:

$$HB = k_{1HB}\alpha + k_{2HB}, \tag{2}$$

where k_{1HB} and k_{2HB} are coefficients which are 0.009 and 28.5, respectively.

The disadvantage of the procedure [20] is the need to conduct additional tests to refine relation (2) when it is used for materials that were not used in its development. In addition, the standard [22], which was used in the development of the procedure [21], has been canceled by the national standardization body (UkrNDNTs state enterprise) as a result of the procedure for harmonizing Ukrainian regulatory documents with European ones. Therefore, today, Brinell hardness is measured according to DSTU ISO 6506-1:2019 [23], according to which hardness is measured using a tungsten carbide ball and is denoted as HBW. By changing the material of the indenter ball, the range of Brinell hardness measurement can be significantly expanded, which makes it possible to apply this method to high-strength steels.

In order to avoid binding to certain materials, expand the range of measured hardness values, and take into account the harmonization of Ukrainian regulatory documents with European ones, the procedure for determining Brinell hardness [21] was improved.

The correlation dependence (3) between the Brinell hardness value and the proportionality parameter of plastic indentation, a, was obtained by the statistical processing of an array of experimental data obtained on the calibrated hardness standards No. B10557 104 HBW, No. B208520 190 HBW, No. B2107179 375 HBW, No. B2109314 527 HBW, and No. B 69221 632.5 HBW (Fig. 2) using a UTM-20HT laboratory tester [17]. The tests were carried out in accordance with the requirements of the standard [23] and the international standard [1] in a cyclic loading mode with a tungsten carbide ball with a diameter of 2.5 mm at a constant indenter speed, while the loading conditions were selected close to the loading conditions in measuring hardness by the DSTU ISO 6506-1:2019 [23] Brinell method. During the test, a continuous process of local material deformation by the indenter was recorded in the form of indentation diagrams in the force–indentation depth coordinates.

Since the scatter of hardness values over the working surface of standards is minimal and the readings of the measuring devices are highly accurate, the correlation dependence obtained in this way can be used in a wide hardness range of structural steels (110–650 HBW):

$$HBW_{ind} = f(\alpha). \tag{3}$$

To select and substantiate the optimal dependence between the indentation parameter a and the Brinell HBW hardness [3], several types of this dependence were considered: linear dependence, second-order polynomial, piecewise linear dependence, and power dependence (7).

Linear dependence

$$HBW_{ind} = k_{1HBW}\alpha + k_{2HBW}, \tag{4}$$

second-order polynomial

$$HBW_{ind} = k_{1HBW}^q \alpha^2 + k_{2HBW}^q \alpha + k_{3HBW}^q, \tag{5}$$

piecewise linear dependence

$$\begin{cases} HBW_{ind} = k_{1HBW}^{l1}\alpha + k_{2HBW}^{l1} & \text{at } \alpha < 40000, \\ HBW_{ind} = k_{1HBW}^{l2}\alpha + k_{2HBW}^{l2} & \text{at } \alpha \geq 40000, \end{cases} \tag{6}$$

power dependence

$$HBW_{ind} = k_{1HBW}^p + k_{2HBW}^p \alpha^{k_{3HBW}^p}. \tag{7}$$

The measurements of traditional Brinell hardness [21] were performed on a TSh-2 stationary hardness tester. To do this, the test conditions were determined: a ball diameter of 2.5 mm, a load value of $F = 187.5$ kg were chosen for the steels under study, and the time of exposure to load was set at 15 s.

Based on the results of the approximation of the experimental data, the coefficients in Eqs. (4)–(7) were determined, the values of which are presented in Table 1. The standard deviation of the correlation equations, which is given in Table 1, was chosen as the criterion for the quality of approximation. The graphical representation of the correlation equations is shown in Fig. 2.

TABLE 1. Values of the Coefficients of Correlation Equations (4)–(7)

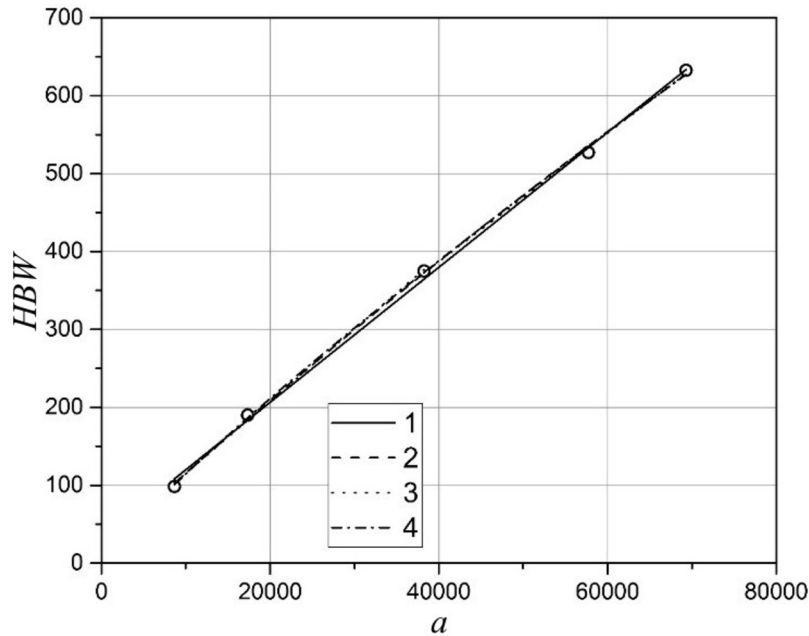| (4)		(5)		(6)		(7)	
Parameter	Value	Parameter	Value	Parameter	Value	Parameter	Value
k_{1HBW}	0.00866	k^q_{1HBW}	$-1.47 \cdot 10^{-8}$	k^{l1}_{1HBW}	0.00926	k^p_{1HBW}	-3.146
k_{2HBW}	33.24	k^q_{2HBW}	$9.798 \cdot 10^{-3}$	k^{l1}_{2HBW}	22.89	k^p_{2HBW}	0.04004
		k^q_{3HBW}	19.07	k^{l2}_{1HBW}	0.00824	k^p_{3HBW}	0.8671
				k^{l2}_{2HBW}	57.63		
Standard deviation values							
0.99854		0.99921		0.99823		0.99945	

Fig. 2. Approximation of the dependence of Brinell hardness on the parameter a for hardness test blocks: (*1*) linear, (*2*) second-order polynomial, (*3*) piecewise linear, and (*4*) power.

From the presented results, we can conclude that the considered correlation dependences give a good fit to experimental data, so for the sake of simplification and ease of practical use, the linear function (4) was taken as the basis.

2. Materials and Specimens. A wide range of different structural, heat-resistant and high-strength steels was used to test the improved procedure:

(i) from rolled plates as delivered: 3 steel (20 mm thick), 20 and 45 steels (12 mm thick), Hardox 450 and Armox 500T steels (10 mm thick);

(ii) from pipelines and shells: 20 steel (seamless feedwater pipeline Ø426×24 mm), 09G2S steel (shell Ø3272×36 mm of a dismantled PV 2500-97-10A high-pressure heater), 16GS steel (dismantled coil Ø630×25 mm with the welded joint of the inlet pipe of a 1RA30S02 check valve DN 600 to the working steam pipeline from PG-3);

(iii) from forgings: 10GN2MFA steel (stock for the control welded joint of the main circulation pipeline Ø990×70 mm), 15Kh2NMFA steel (vessels, covers and other components of NPP reactor units).

The specimens for hardness measurements were made on a milling machine from blanks cut from metal templates on a band saw using cooling. After milling, the specimens were subjected to grinding and subsequent polishing of the working surface to a roughness of $R_z = 0.25$ μm.

3. Research Results. The Brinell HBW hardness values of the above-mentioned steels were obtained by averaging the results of 10 measurements in accordance with [21] and are given in Table 2. It can be seen that the deviation of the Brinell hardness values obtained using the improved procedure and the traditional method [20] does not exceed 4.5% and is within the hardness determination error in accordance with state standards.

TABLE 2. Brinell Hardness Values

Steel grade	HBW		Deviation in %
	Hardness tester TSh-2 [21]	Improved procedure	from the hardness results according to [21]
Rolled plates			
3	107.3	106.8	−0.5
20	117.3	121.5	3.6
45	205.5	196.7	−3.8
Hardox 450	428.0	424.2	−0.9
Armox 500T	499.0	490.2	−1.8
Pipelines and shells			
20	146.3	140.9	−3.7
09G2S	135.5	139.2	2.8
16GS	161.4	167.8	3.9
Forgings			
15Kh2NMFA	190.2	184.8	−2.9
10GN2MFA	179.0	183.9	2.7

In Fig. 3, the results of Brinell hardness measurements according to DSTU EN ISO 6506-1:2019 [23] were plotted for clarity versus the data obtained from the results of instrumented indentation using the improved procedure. The dashed lines show the 5% interval between the hardness values obtained by the improved procedure and the conventional Brinell method.
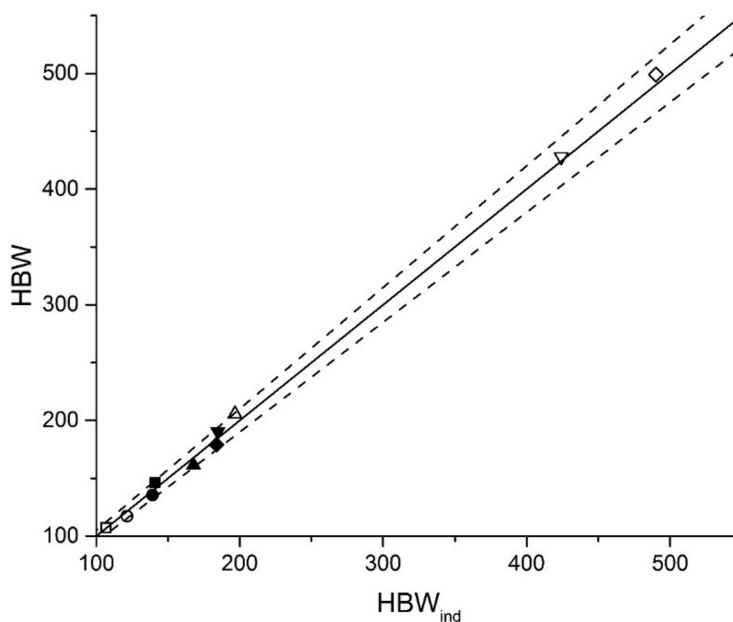

Fig. 3. Comparison of Brinell hardness values determined with a TSh-2 stationary hardness tester (HBW) and the method of instrumented indentation (HBW_{ind}) [Steels: rolled plates: (○) 3, (□) 20, (△) 45, (▽) Hardox 450, (◇) Armox 500T; pipelines: (●) 20, (■) 09G2S, (▲) 16GS; forgings: (▼) 10GN2MFA, (◆) 15X2NMFA.]

Thus, the developed procedure can be successfully used to diagnose the current state of materials of engineering products during production and operation.

Conclusions. Based on the results of the research carried out, a procedure for determining the Brinell hardness by instrumented indentation was improved, which made it possible to avoid binding to certain materials by using calibrated hardness standards, expand the measurement range (110–650 HBW) and take into account the current requirements of Ukrainian regulatory documents.

The improved procedure for determining the Brinell hardness of structural materials by instrumented indentation was evaluated. The research results show that the deviation of the values determined by the improved procedure from the results of Brinell hardness measurements does not exceed 3.9 %.

The developed equipment and the improved procedure can be used in the laboratories of research and educational institutes, central factory laboratories and specialized divisions of various subordination and other organizations involved in monitoring the condition of operating critical equipment and setting its further service life both in the laboratory and in the field.

Conflict of Interests. All authors declare that they have no conflicts of interest.

Author Kharchenko V. V. is the member of the Editorial Board of Strength of Materials journal. The paper was handled by another Editor and has undergone a rigorous peer review process. Kharchenko V. V. was not involved in the journal's peer review, or decisions related to this manuscript.

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