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METROLOGICAL CHARACTERISTICS OF THE NATIONAL SHORE D SCALE HARDNESS STANDARD

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Abstract - Design specifics and study results are provided for the new National Shore D scale hardness standard. At the metrological study of the standard the calculations of uncertainty in measurements with two methods are considered: in accordance with the international guide on expression of uncertainty in measurement and in accordance with the principles based on the scales of order properties.

According to the metrological study, the standard ensures the reproduction and dissemination of the scale in the actually used range of HSD numbers of 20 to 102 with an HSD uncertainty of no more than 0.5.

Keywords: Shore D hardness scale, uncertainty analysis, scales of order.

1.INTRODUCTION

The need to inspect quality of metal products requires constant improvement of the metrological support for metal hardness measurements with various scales, including the hammer rebound method (Shore scale). The method and the tester for measuring hardness with the rebound were developed by A.Shore [1] while the rebound hardness theory was proposed by D.Tabor [2]. There are various designs of Shore hardness testers. But the most convenient and popular in Russia and other countries is the D-type design of the Shore hardness tester. D-type hardness testers have become the only instruments in the world used for on-line hardness inspection of large-size parts, including forming rolls.

Hardness measurements with Shore D scale are based on the dynamic measurement method when the hardness number is determined by the rebound height of the standard hammer dropped to a sample block from the fixed height. The Shore D scale metal hardness measurement method, the technical requirements for hardness testers and the Shore hardness blocks are uniformly standardized in many industrial countries. But, unfortunately, there is no international standard for the Shore D scale itself in existence.

2. COMPOSITION AND THE PRINCIPLE OF OPERATION

In accordance with the development plan for the Russian base of standards the equipment set of the Shore D scale metal hardness standard was developed and studied in All-Russian Scientific and Research Institute for Physical-Technical and Radiotechnical Measurements which ensures measurement of the metal Shore D hardness scale HSD number values in the range of 20 to 102. The standard is intended for reproduction of the Shore D scale and dissemination of this scale with the reference hardness blocks to hardness testers in order to ensure uniformity of measurements. The standard is a set of devices including:

- the stationary system with the hammer, the device for measuring the rebound height of the hammer and the device for vertically orienting the testing head which contains the hammer;
- the electronic unit for automating the measurement process and interfacing the control computer with the stationary system;
- the microscope for selecting a test point on the hardness block.

The HSD number is proportional to the hammer rebound height

$$HSD = K \frac{h_2}{h_1},$$

where K is the proportionality factor, h_1 is the hammer drop height, h_2 is the hammer rebound height. Since the direct measurement of the hammer rebound height with the required precision is difficult, h_2 is determined by the time interval between the first and second impacts of the hammer according to the following formula [3]:

$$h_2 = \frac{g(t_1 - t_2)^2}{8},$$

where g is the gravitational acceleration, t_1 is the time interval between the first and second impacts of the hammer, t_2 is the time period of the hammer being in contact with the sample block.

The basis of the standard is the stationary D-type Shore system with the hammer and the device for measuring the hammer rebound height. The system consists of the 30-kg base plate, the testing head with the diamond hammer and the lever for clamping the hardness block to the base plate. The ratio of the lever arms is 1:10 and with the weight fitting it provides the clamping load of (100±5) N to (500±25) N. The illumination microscope is located on the standard bench for selecting a test point on the hardness block. In accordance with requirements of the national standards the weight m, the rounding-off radius R and the drop height h_1 of the diamond hammer should have the values with the admissible deviations as shown in Table 1.

TABLE 1.Calculation of the correction and uncertainty in measurement at the National Shore D scale hardness standard for HSD levels of 88 to 102

No.	Parameter x_i			Certificate data			Sensitivity coefficient	Measured hardness		
	Desig-nation	Meas. unit	x_{in}	$\Delta x_i = x_i - x_{in}$	$U_i\ (2\sigma)$	ν_i	$c_i = \frac{\partial HSD}{\partial x_i}$	Δ_iHSD	$u_i^2(HSD)$	$u_i^4(HSD)/\nu_i$
1	m	g	36,0	$-4{,}2 \cdot 10^{-1}$	10^{-2}	20	$6 \cdot 10^{-1}$	$-2{,}5 \cdot 10^{-1}$	$9 \cdot 10^{-6}$	$4{,}1 \cdot 10^{-12}$
2	R	m	1,0	10^{-2}	$4 \cdot 10^{-3}$	20	$2{,}1 \cdot 10^{1}$	$2{,}1 \cdot 10^{-1}$	$1{,}8 \cdot 10^{-3}$	$1{,}6 \cdot 10^{-7}$
3	t1	sec	-	-	$6 \cdot 10^{-7}$	10	10^{5}	-	$9 \cdot 10^{-4}$	$8{,}1 \cdot 10^{-8}$
4	t2	sec	-	-	$6 \cdot 10^{-7}$	10	$3 \cdot 10^{4}$	-	$8{,}1 \cdot 10^{-5}$	$6{,}4 \cdot 10^{-10}$
5	h_1	mm	19,0	$2 \cdot 10^{-2}$	10^{-2}	20	$2{,}4 \cdot 10^{-2}$	$4{,}8 \cdot 10^{-4}$	$1{,}5 \cdot 10^{-8}$	10^{-17}
6	g	mm/sec^2	-	-	$5 \cdot 10^{-5}$	10	5	-	$1{,}6 \cdot 10^{-8}$	$2{,}6 \cdot 10^{-17}$
7	$\sum$							$\Delta = -0{,}04$	$2{,}8 \cdot 10^{-3}$	
8	Standard uncertainty, u_m								0,05	
9	Effective degrees of freedom, ν_{eff}								32	
10	Coverage factor, k								2	
11	Expanded uncertainty, $U = ku_m$								0.1	
12	$\Delta H_i = c_i \cdot \Delta x_i$ and $u_i^2(H) = c_i^2 \left(\frac{U_i(2\sigma)}{2} \right)^2$									

Designations: x_{in} – nominal parameter values as per the national standards, x_i – result of the VNIIFTRI standard parameter measurement, $\Delta x_i = x_i - x_{in}$ – actual deviation of parameter x_i from its nominal value of the VNIIFTRI standard, $U_i(2\sigma)$ – expanded (k=2) uncertainty in measurement of parameter x_i of the VNIIFTRI standard, $\Delta = \sum \Delta_i$HSD – correction to HSD measurement results at the VNIIFTRI standard, g = 0,98156 – local gravitational acceleration (for Moscow).

The standard testing head design ensures free drop of the hammer. The fixed height of the hammer drop is determined structurally and is not dependent on the hardness block height.

A piezoelectric cell is used as the detector of the signals corresponding to moments of the hammer's first and second impacts. The piezoelectric cell signals are initially processed in the time interval measuring unit. The pulse whose duration is equal to the time interval between the fist and second impacts of the hammer is fed from the time interval measuring unit output to the board input of the microcontroller interfacing the time interval measuring unit with a PC. The microcontroller board with the quartz frequency generator is installed in the time measuring unit module. The standard automation system provides for measuring the time interval with the controller and mathematical processing of several series of such measurements by the computer linked to the controller.

3. RESULTS

Table 1 shows the calculation data on the correction and uncertainty in measurement at the National standard for HSD hardness number range of 88 to 102. The calculation was based on *Guide to the Expression of Uncertainty in Measurement* [4] and *EA-10/16 Guidelines* [5]. Tables 1 and 2 show the parameters involved in estimation of uncertainty for the standard [6] and regulating the Shore D scale hardness measurement method as per GOST 23273-78 "Metals and Alloys. Hardness Measurement with the Hammer Rebound Method (by Shore)". Effect of such parameters as the impact energy, elasticity of the hammer and sample block, correlation of the hammer and sample block weights, the ambient temperature, the clamping force applied to the hardness block studied in detail in the papers [7, 8] and in the review work [9] is insignificant in comparison with the effect of the parameters included in Table 1.

Experimental data on sensitivity coefficients c_i [6] were used in the calculations. The dominating contribution to the summary uncertainty of the component specified by the diamond hammer rounding-off radius from its nominal value is evident. The data provided in Table 1 show that in measuring hardness at the standard within the given range of Shore D scale correction ΔHSD equal to – 0,04 with expanded uncertainty 0,1 is obtained. Similar studies have shown that this uncertainty value is the maximum for other HSD hardness number ranges of 23 to 37 and of 53 to 67.

Table 2 shows calculation of the ultimate possible correction to the measurement results at the standard for the maximum deviation values $\Delta_P x_i$ admissible in standards. The calculation shows that the values of $\Delta_P x_i$ stated in Table 2 provide significant corrections of ΔHSD from minus 2,4 to plus 1,8.

TABLE 2. Maximum admissible correction to measurements at the National Shore D scale hardness standard

No.	Parameter x_i				Sensitivity coefficient $c_i = \frac{\partial HSD}{\partial x_i}$	Admissible correction $\Delta_i HSD$
	Design-ation	Mea sure unit	x_{in}	$\Delta_P x_i$		
1.	m	g	36,0	− 0.5	$6 \cdot 10^{-1}$	− 0,3
2.	R	m	1,0	± 0.1	$2,1 \cdot 10^{1}$	± 2,1
3.	H_1	mm	19,0	± 0.5	$2,4 \cdot 10^{-2}$	± 0,01
Maximum admissible deviation, Δ_{max}						− 2,4 + 1,8

Designation: $\Delta_P x_i$ – parameter x_i deviation from x_{in} admissible in the national standard.

Table 3 shows the data on measuring HSD of reference hardness block No. 3/01 at the National standard by Shore D scale. Uncertainty of calibrating the reference hardness blocks at the National standard is calculated by the formula [5]:

$$u_{bm} = \sqrt{u_m^2 + s_b^2}$$

where u_m=0,05 is the standard uncertainty of the primary standard, s_b=0,095 is the standard deviation of the HSD measurement calculated according to the data in Table 3. Then the calibration uncertainty of the reference hardness block is equal to u_{bm} = 0,11, and the result of the HSD measurement for hardness block No. 3/01 at the coverage factor κ=2 will amount to:

HSD = (99,2 ± 0,22).

TABLE 3. Data for measuring reference hardness block No. 3/01 at the National Shore D scale standard

Number of block working surface	Data on series of HSD measurements					Mean value of HSD_b	Median of value series HSD_m
	1	2	3	4	5		
I	99,0	99,0	99,2	99,3	99,5	99,2	99,2
II	99,0	99,1	99,1	99,3	99,4	99,2	99,1

At calculating the calibration uncertainty of the reference hardness block with the second method based on the scales of order properties [10] the fact is taken into account that all hardness measurement scales in accordance with the general theory of measurement are the scales of order devoid of proportionality. So the "measurement unit" notion is not applicable to them and statistics of the arithmetic mean and quadratic mean deviation are not adequate for them. For these scales it would be correct to take the median [11] as the measurement result. The median is invariant to principally possible monotonous transformations of scales of order. It is clear that, in addition to uncertainty in measurements at the standard, the spread of the block hardness across its surface is included in the repeatability of the HSD number values shown in Table 3. It is proposed to express the uncertainty for hardness scales as the repeatability of hardness number values from H_{min} to H_{max}, changed up and down on the scale to Δ_m – the border of uncertainty in reproducibility of the scale by the standard (the data sheet of the standard), i.e., from $H_{min} - \Delta_m$ to $H_{max} + \Delta_m$ [12]. By the data in Table 1 we take $\Delta_m = |\Delta| + U$ = 0,04 + 0,1 = 0,14. Then we obtain the uncertainty in the HSD measurement of (99,0 – 0,14) to (99,5 + 0,14). Thus, for hardness block No. № 3/01 the hardness number is HSD_m = 99,15 with the HSD uncertainty of 98,86 to 99,64.

4. CONCLUSION

The results of uncertainty estimation in measurements of hardness numbers obtained with these different methods are quite compatible. A half of the uncertainty interval with the second calculation method should be, in principle, close to $2u_{bm}$ with the first calculation method, and this is what is in fact obtained: (99,64 – 98,86) / 4 = 0,2 ≈ 0,22. Thus, the standard ensures the reproducibility and dissemination of the scale in the actually used range of HSD of 20 to 102 with an HSD uncertainty of no more than 0,5.

The method of estimating the result and the calibration uncertainty of the hardness blocks by the median and repeatability of certain experimental data is preferable, since it does not contain any operations in conflict with the theory of measurements and, being simple, provides the calibration uncertainty values which are close to calculations according to the EA-10/16 guidelines.

The data concerning results of the study of the standard metrological characteristics demonstrate the need to establish a uniform international standard for the Shore D scale hardness measurement method for ensuring uniformity and increased accuracy of measurements. With this, it is expedient to set stricter admissible parameter deviations for primary standard equipment than for industrial Shore D-type testers.

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