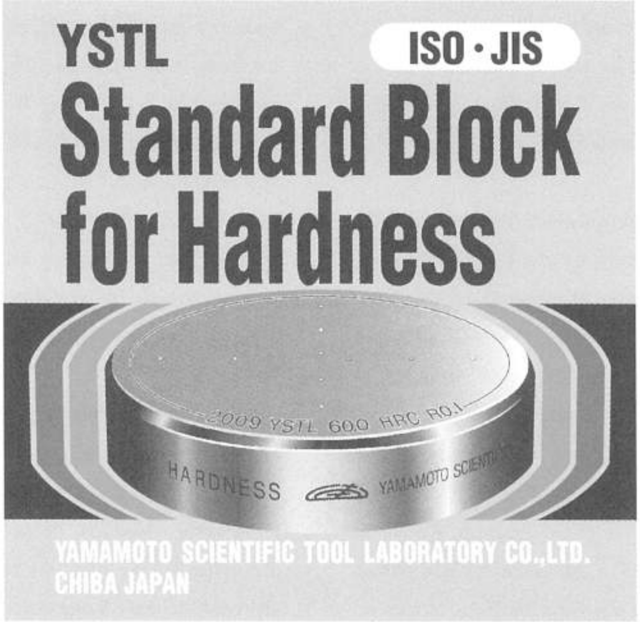
Role and use of standard hardness blocks

How to make a hardness test in the right way



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Role and use of standard hardness blocks

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1. Introduction

A hardness test is a mechanical test that is important for guaranteeing the strength of industrial products. A standard hardness block is a standard test piece used to check if and ensure that a hardness tester and its use are normal. No matter how well a tester functions, it would be natural to suspect that the tester is no longer sufficiently accurate after repeated use. Therefore, it is quite natural that one would think that any abnormal changes to the status of a tester and testing procedures can be identified by previously testing the most ideal test piece possible with the most ideal hardness tester possible and comparing the results with those of hardness tests on a daily basis. In other words, a standard hardness block can be described as a convenient tool for guaranteeing the reliability of a hardness test.

In Japan, Shoichi Yamamoto succeeded in domestically manufacturing standard hardness blocks for the first time in 1939, with the support of experts mostly in metallurgical engineering. After World War II, Shoichi and Hiroshi Yamamoto (father and son) founded a company that specializes in manufacturing standard hardness blocks—the only company of its kind in the world. With the support of the Hardness Study Group, which is currently the Material Testing Research Association of Japan (MTRAJ) [1], the company has grown to supply as many as 30,000 standard hardness blocks of about 140 types internationally.

Section 2 of this article presents an overview of hardness tests and several views on standards of hardness. Section 3 presents the roles and characteristics of standard blocks for hardness. And, Section 4 details the method of indirect verification via hardness standard blocks for daily inspections of hardness testers.

2. Hardness Test Methods

Hardness is a concept for showing the strength of a material and a physical property that is less concretizable. O'Neil compared the difficulty of describing hardness in quantitative and concrete terms to describing the roughness of the sea[2), 3)]. Generally, hardness is evaluated by pushing a hard and sharp object—called an indenter—against a test material with a certain amount of force—called the test load—and measuring the difficulty with which the indenter penetrates or the nick in the material made by the indenter—called an indentation—to describe hardness as the extent of the test material's resistance to deformation. Another method of evaluating hardness is based on the energy consumed to deform a test specimen when it is impacted by an indenter. The current hardness test methods that involve deforming a test sample with an indenter are classified into either of the two types of test mentioned above: static indentation test and rebound (also called dynamic indentation) test. The former includes Brinell, Rockwell, Vickers, and instrumented indentation tests. The latter includes Shore and Leeb tests. In addition to these, there is a method called the scratch hardness test, but it is not discussed in this article.

2.1 The Standard of Hardness Based on Definition

The hardness value of a standard hardness block cannot serve as an absolute standard of hardness. The hardness of a material depends on not only the basic physical properties of the material but also its trace constituents, segregation, and microscopic structure, and how it is heat-treated and/or machined. In addition, not a few materials have a high strain rate sensitivity or tendency to cause creep deformation. Under different loading conditions, different hardness measurements are obtained from the same material, so it is theoretically impossible to rely on a hardness block to get an absolute value of hardness. The value indicated on a hardness reference block is nothing but the best possible result of a hardness test conducted under the conditions provided for in the applicable industrial standards, and as such it serves as a standard value for the sake of convenience. Therefore,

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hardness blocks should be used only as a guide for daily inspections of hardness testers.

Because a value of hardness is an industrial quantity that is only available by performing a hardness test in accordance with predetermined testing method and conditions, the definition of the testing method itself can constitute a standard of hardness. Unlike a physical quantity, there is no inherent unit for hardness. This is easily understandable from the facts that the four arithmetic operations of hardness measurements do not make sense and the values of 100 HRC and 130 HRB are equal to infinite values in Rockwell hardness.

To sum up, a standard of hardness relies on the definition of the testing method theoretically, and in practice, the accuracy of the test load (force), the dimensional measurements (length) of indentations, and other factors[4].

2.2 Direct Verification Based on Force and Length

A hardness value is a quantity obtained by measuring the amount of deformation in terms of length that results from applying force through an indenter onto a test sample. The accuracy of such force and length and the indenter's geometry is called direct accuracy, because it is directly related to the accuracy of hardness measurements. Verifying the direct accuracy of a hardness tester is then called direct verification. Calibration to correct errors in the direct accuracy is possible, but the hardness measurements indicated by the tester cannot be adjusted (calibrated) directly.

2.3 Indirect Verification (Comprehensive Error Check) Based on Hardness Blocks

As described above, direct accuracy is an important concept in hardness tests, along with the definition of a test method. However, it is not practical to conduct frequent direct verifications to confirm the accuracy of a test load and the length-measuring system of a hardness tester. Therefore, the results of testing a standard hardness block are checked on a daily basis to confirm the accuracy of the tester indirectly. This is called indirect verification using hardness blocks.

Even a hardness tester for which direct accuracy has been confirmed can produce erroneous test results if loading conditions and operating procedures are inappropriate or if an indenter is defective or mounted inappropriately onto the tester. The daily inspection of hardness testers using hardness blocks is also called a comprehensive error check, because it provides a means for evaluating not only the direct accuracy of a tester but also whether the test is conducted appropriately from a comprehensive viewpoint.

3. The Roles and Characteristics of Hardness Blocks

As mentioned in the previous section, a standard hardness block is used to check the status of a hardness tester and the appropriateness of the testing operation from a comprehensive viewpoint based on the results of a test performed on the block. Accordingly, a hardness block must be able to provide a basis of judgment as to whether the tester's indicated values:

(1) are within a range of normal values,

(2) do not vary abnormally, and

(3) do not change extraordinarily over time.

To achieve that, the test surface of a hardness block must ideally be uniform in hardness; the hardness values obtainable with the block must not undergo change over time due to the quality of the block material; and, the standard value indicated on the block as the result of a hardness test made on the block must be highly reliable.

3.1 Hardness Uniformity of Hardness Blocks

The most important feature of a standard hardness block is the uniformity of its hardness. Insufficient hardness uniformity would require more test points and higher labor costs for indirect verification, and the resulting test results would not necessarily be reliable. To ensure high quality and economic management of hardness tests, uniform hardness of a standard hardness block is essential.

A block's hardness uniformity largely depends on the quality of the material and how it is prepared, as well as how it is heat-treated or otherwise processed. Therefore, a standard hardness block is made of any of the materials dedicated for that purpose, including high-purity steel. These block materials must be carefully selected following a close examination of quality and availability. Table 1 shows the specifications of all 140 types of hardness standard block supplied by YSTL, including the material and hardness uniformity of the blocks. Figure 1 shows the microscopic structure of a representative standard block. The block material and heat treatment conditions are carefully selected to ensure a uniform

Table 1 Specifications of standard blocks

Assortment	Hardness value	Tolerance	Calibration number(n)	Variation (R=Max.-Min)	Materials (JIS notation)	Dimention (mm)	Finished surface	Standard based
HMV (1, 0.1)	1650	±10%	4 (2×2)	2% (HV1)	Si_3N_4	□10×5	□	JIS B 7735
HMV (1,0.1,0.01)	900, 800, **700**, 600, **500**	±15	6 (3×2)	5% (HV0.1)	SK85	ϕ25×6	□	JIS B 7735
〃	400, 300, **200** (Be Copper)	±15	〃	〃	C1720P	ϕ25×6 (2)	□	〃
〃	100 (C2600P), 40 (C1020P),	±10	〃	7 (100HV0.1), 4 (40HV0.1)	←	ϕ25×5 ※	□	〃
HMV (0.1,0.01,0.001)	30 (AU)	±10	〃	4 (HV0.1)	Au	ϕ25×5 (0.8)	□	〃
UMV (0.01, 0.002)	900, 700 (Berkovich 9.8mN tested)	±20%	6 (3×2)	10% (HV0.01)	SK85	ϕ25×6	■	JIS B 7735
〃 (0.01, 0.001)	500, 200 (〃)	〃	〃	〃	SK85,C1720P	ϕ25×6 (2)	■	〃
★Nano indentation Hardness Blocks (HV0.01, 0.001 Berkovich 9.8mN tested)		APPROX430 HV0.001	6 (3×2 HV, Nano)		Single Crystal Tungsten	ϕ25×6 (W: ϕ9×3)	■	JIS B 7735
HV (30, 1)	1000 (SK120), 900, 800, **700**	±15	10 (5×2)/HV30,10	1.5%	SKS3	ϕ64×15	○	JIS B 7735
HV (10,1)	600, **500**, 400, 300, **200** (SK85), 150 (S45C)	〃	6 (3×2)/HV1	〃	←	〃	○	〃
〃	100 (C2600P), 40 (C1020P)	±10		(150HV and below 2.2%)	←	ϕ64×10	○	〃
HS	100 (SK120), 95, **90**, 80, 70, **60**, 50, 40, **30**	±2	HV10 (5×2)	R VHS≦1.5 (70HS and below 1.2)	SK85	ϕ64×15	○	JIS B 7731
〃	20 (S20C), 7 (C1020P ϕ64×10)	〃	HS10 (5×2)	⊿HS (HS−VHS) ≦0.5	←	〃	○	〃
HL	HLE (Dia) 850, 800, 700, 600, 500	±15	(HV Calibration)		SK85	ϕ115×33	○	JIS B 7731 Related
	HLD (WC) 880, 830, 730, 630, 520	〃			〃	〃	○	
HR C	70 (SK120), 67, 64, 62, **60**	±1	10 (5×2)	0.2	SKS3	ϕ64×15	○	JIS B 7730
〃	57, 55, **50**, 45, **40**, 35, **30**, 25, 20, 10	〃	〃	(40RC and below 0.3)	SK85	〃	○	〃
HR A	87, 85, 83, **81**, 78, 75, 71, **65**, 56	〃	〃	0.3	Same as HRC	〃	○	〃
HR 30N	83, **81**, 78, 73, **67**, 60, 55, 50, 41	〃	〃	0.6	〃	〃	○	〃
HR 15N (45N)	92, **90**, 87, 85, **80**, 75 (43) (23)	〃	〃	〃	〃	〃	○	〃
HR B	100, 95, **90**	±2	10 (5×2)	0.8	SK85	ϕ64×10	△	JIS B 7730
〃	**82**, 72, **62**, 52, **42**, 32	〃	〃	(50RB and below 1.0)	C2600P	〃	△	〃
HR 30 T	78, 72, 62, **52**, 42, 38, 32	〃	〃	1.0	Same as HRB	〃	○	〃
HR 15 T	87, 82, **78**	〃	〃	〃	〃	〃	○	〃
HR (E·M·L·R·F·S)	HRE**90** HRM107 HRL118 HRR123 HRF90	〃	〃	〃	(100HV)	〃	○	JIS K 7202
〃	HRM67 HRL92 HRR**105** HRS90	〃	〃	〃	(40HV)	〃	○	〃
HBW (10/3000)	600, 550, 500, 450, **400**, 350	±15	6 (3×2)	1.5%	SK85	ϕ115×18	●	JIS B 7736
HB (10/3000)	**300**, 250, 229 (d=4mm), **200**, 180	〃	〃	〃	〃	〃	●	〃
	HB (10/3000) 150, HB (10/500) 125	〃	〃	2.5%	S45C	〃	●	〃
	HB (10/500) 100	〃	〃	3%	S10C	〃	●	〃

Finished test surface; ●Fine grinding, △plate lapping, ○Buffing, □Super finish, ■Super finish(fine), ※ϕ25×6
New Test Blocks (N. T. B.)※(for Spot Anvil)◇Export only

HRC	67, 64, 62, 60	±1	6 (3×2)	ϕ50.8×6.4 (ϕ2″×1/4″)	(ASTM E-18)
HRC	55, 50, 45, 40, 35, 30, 25, 20				

structure for each test method for which the block is intended. The high hardness uniformity of YSTL blocks can be seen from the standard deviations of hardness values of some of the most popular kinds of blocks produced in recent years:

0.03 HRC or less for 60 HRC blocks

0.05 HRC or less for 30 HRC blocks

These values of variations among hardness values, or hardness uniformity, were obtained from as many as 500 blocks, not a limited number of blocks[5]. This high uniformity, or small variation, of hardness values reflects not only the high hardness uniformity of standard blocks but also the performance of a standard hardness tester that is used for testing the hardness blocks. This suggests that good hardness testers are required for developing and manufacturing high-accuracy hardness blocks, and that good-quality hardness blocks are required for conducting highly reliable hardness tests.

3.2 Hardness Stability of Hardness Blocks

Hardness blocks are not only required to be uniform in hardness, but the hardness must also not change over time due to block material, heat treatment, and/or machining process. To prevent such changes, for example, hard steel blocks are given a subzero treatment, because their hardness can change over time if the quenched structure has residual austenite. Soft hardness blocks are also treated to prevent changes in hardness attributable to the

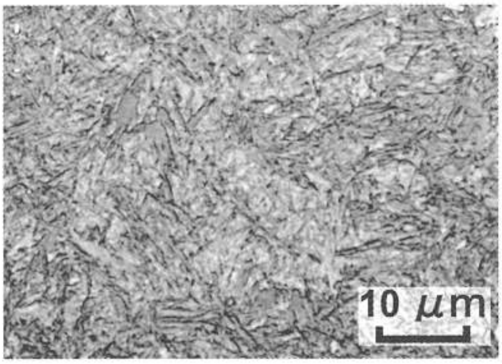
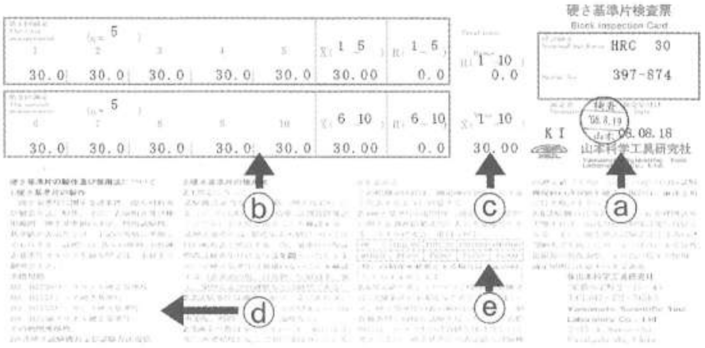


Fig 1 Uniformly hardened microstructure of standard block made of eutectoid carbon steel

Fig. 2 Outside Appearance of HRC Block
The numbers 1 to 10 on the test surface represent five test points each for two testers. (a) shows the standard value and other information; b) is the serial number.


硬さ基準片検査票
Block inspection Card

1	2	3	4	5	X(1～5)	R(1～5)
30.0	30.0	30.0	30.0	30.0	30.00	0.0
6	7	8	9	10	X(6～10)	R(6～10)
30.0	30.0	30.0	30.0	30.0	30.00	0.0

R(1～10) 0.0
X(1～10) 30.00

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Fig. 3 Information on the Front Face (a, b and c) and the Reverse Face (d and e) of the HRC Block Inspection Card
(a) Serial number, and dates tested and inspected; (b) Five test results each for two testers; (c) 10-point test result; (d) JIS compliance; (e) Durability, etc.

release of stress. The extent of changes to the hardness of hardness blocks thus treated may be an interesting issue that draws scientific attention, but as far as we have confirmed, no change of hardness is detectable with the current hardness testing capacity for YSTL hardness blocks that have passed the warranty period of three years.

3.3 Indicating Universal Hardness Values Based on JIS and ISO Standards

Because it is made of some sort of material, a hardness block cannot be immune from the strain rate dependency and creep deformation mentioned earlier. Therefore, needless to say, a test for determining the standard hardness value to be indicated on a standard hardness block (hereinafter called standard value determination test) must be conducted with the loading velocity and test force dwell time specified in the JIS or ISO standard for hardness test methods. The standard value determination test used to apply special testing conditions that differ from those for general hardness tests, but this has been reviewed in recent years as reflected in JIS and ISO standards for hardness blocks. The hardness measurements obtainable for an ideal hardness block—for which the standard value is determined through a test under JIS/ISO-specified loading conditions using the correct indenter and a standard hardness tester with acceptable direct accuracy—when it is tested with the correct testing machine and loading conditions should automatically be expected to equal the standard value indicated on the block. This may seem to be quite natural, but paradoxically provides an extremely important suggestion.

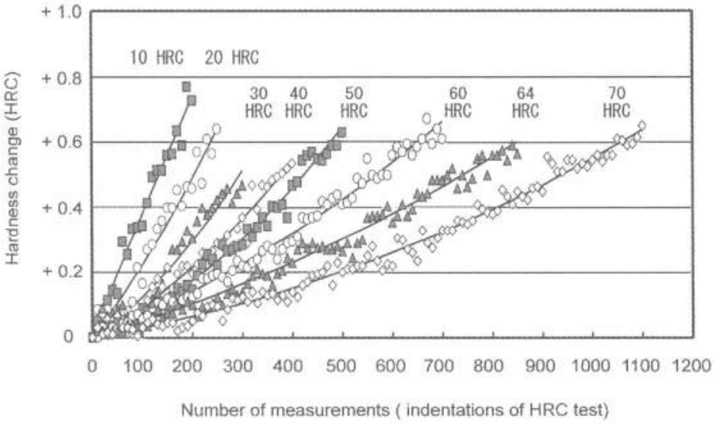

Fig. 4 Variations of Measurements with an Increase of HRC Test Points

Table 2: Durability of Standard Hardness Blocks
(Results of Investigation by Hardness Study Group No. 14 Committee)

Hardness	60HRC	30HRC	90HRB	60HRB
The Upper Limit of Test Points (approx.)	500	260	250	200

Fig. 5: Before and After Rust-preventing Oil is Removed

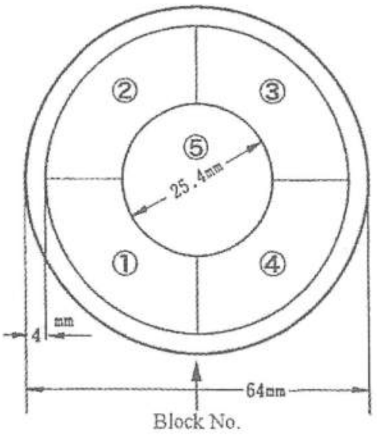

Fig.6 Sectioning of Block Test Surface

The standard value determination test can also be seen as an act for indicating a universal hardness value on a standard hardness block using standard hardness testers with excellent direct accuracy and following JIS/ISO-based universal testing conditions.

3.4 Lot-based Production of Hardness Blocks for Stable Quality

The lot production system (basically 20 blocks per lot) is adopted for the entire process of manufacturing all types of YSTL block, irrespective of the size of demand, to secure reliability of quality and standard values. In particular, the final process of testing to determine standard values is done carefully using standard hardness testers and indenters for which direct accuracy is verified semiannually in accordance with applicable standards for hardness blocks.

4. How to Use Hardness Blocks

This section presents the detailed procedures for indirectly verifying a hardness-testing machine using JIS/ISO-compliant hardness blocks. For verification, one should select one block each from the high, medium, and low hardness levels of the scale to be used. If the test is conducted within a certain range of hardness, a block whose hardness is close to that of the tested part or product may be selected. As shown in Table 1, the nominal hardness of hardness blocks has a certain range of tolerance. When the specimen's hardness is expected to be around 60 HRC, for example, even if the nominal hardness of a hardness block to be used is actually 59, 60, or 61 HRC, that would not affect the results of indirect verification.

4.1 Confirmation of a Hardness Block before Indirect Verification

As shown in Figure 2, the side face of a hardness block is engraved with the serial number of the block, and its standard hardness value is indicated on the test surface. Figure 3 shows an example of the Block Inspection Card that accompanies each block. Before conducting an indirect verification, confirm the following.

(1) The serial number shown on the block itself is identical to the number that appears on its inspection card.

(2) The warranty period of the block

As described in Section 3.2, a hardness block is processed so as not to experience changes of hardness due to its material. However, it is a consumable tool by nature, so a warranty period is set at three years starting from the date of inspection stamped on the inspection card. During the warranty period, the first block produced in the same lot is stored at the manufacturer so that this warranty block can be compared to the rest of the blocks in the lot to check their status or microscopic structure if so requested by their users.

(3) The block to be used complies with applicable JIS/ISO standards.

The standard to which the block complies is shown on the reverse side of its inspection card. Blocks that conform to any standards other than JIS cannot be used for indirectly verifying general hardness testing machines.

(4) The rust-preventing oil on the top and bottom faces of the block has been removed.

New steel blocks are coated with rust-preventing oil on the top and bottom surfaces. This oil must be completely wiped off with a clean cloth or equivalent before using the block (See Figure 5).

(5) The status of the block's bottom face

Especially for tests based on the depth of indentation to obtain hardness measurements, such as Rockwell, the bottom face of the block must be free from any foreign objects, including dirt, rust, scratches, oil and dust, as well as indentations.

(6) The status of a block's top test surface and number of

indentations

The top test face must be free from anything that may affect the test results, including scratches, rust, and dirt. As shown in Figure 4, too many indentations will lead to higher hardness measurements with larger variations. A hardness block for which the number of indentations has reached the limit of useful life as shown in Table 2 must be replaced with a new one. If one desires stricter control of hardness blocks than specified by JIS, about half of the numbers of indentations given in Table 2 should be set as the guidelines for timing replacement [6].

4.2 Confirmation of a Testing Machine before Indirect Verification

There are many types of hardness testing machine according to the test methods for which they are intended. For details on how to use a particular hardness tester, one should follow the instructions given by a person who is familiar with the tester or in the manual attached to the tester. In addition, the following items should be confirmed in general before conducting an indirect verification of a hardness tester.

(1) Effective period of direct verification

Before indirect verification is discussed, it should be confirmed that the hardness tester undergoes direct verification on a periodic basis (once a year, for example).

(2) Hardness scale and test force selected

The appropriate hardness scale and test force should be selected according to the hardness, dimensions (especially thickness), and material of the test sample. For a hardness tester with a leverage-based loading mechanism, even a slight misalignment of the loading dial could affect the test force applied.

(3) Status of diamond indenter

It should be confirmed that a diamond indenter has no defects or scratches. In the case of Vickers diamond indenters, repeated use may abrade the edge lines of the indenter, rounding off the corners of indentations.

(4) Ball indenter selected and no defects found in the indenter

For Brinell hardness tests, cemented carbide ball indenters must be used. Meanwhile, Rockwell hardness tests can be conducted with either a steel or cemented carbide ball indenter as mentioned later, but the HRB test results can differ by nearly 1 HRB between the two types of ball indenter (See Figure 9). Therefore, the utmost care must be taken not to mistake one for the other. The measurement results with a steel ball indenter must be marked with the letter S following the hardness code (such as HRBS), whereas those with a cemented carbide ball indenter must be marked with the letter W (such as HRBW).

If the head of a ball that protrudes from the indenter holder does not rotate with finger pressure, the ball indenter might have rusted or been permanently deformed (see 5.4). Such an indenter must be replaced with a new one.

(5) Status of the anvil

The anvil of a hardness tester must not develop backlash or slackness. In particular, the bottom surface of the anvil of a Rockwell hardness tester should be free from any foreign objects, including dirt, rust, scratches, and oil, as well as indentations. Because thoughtless lubrication of the part where the anvil is attached to the tester or around the lifting screw could spread the oil into portions related to indentation depth measurement, such lubrication if necessary must be conducted in accordance with the instructions of experts or applicable instruction manuals.

(6) Temperatures of tester, specimen, block, and testing environment

The ambient temperature for hardness tests must be 10-35°C for general conditions, and 18-23°C for highly controlled conditions. If the temperature is outside these ranges, such should be stated in the test report. It is recommended that tester, block, and test specimen be warmed up sufficiently to be within the above temperature range. Testing environments with highly variable temperatures could affect the performance of a tester and the hardness of a standard block.

4.3 Indirect Verification by Testing a Standard Hardness Block

The JIS/ISO standards prescribe a daily inspection by testing a standard hardness block at five points before testing of products or specimens It is sufficient that the average of the five measurements is rounded to three effective digits. The five-point measurement procedures

Table 3 Tolerances for Indirect Verification of Hardness Testing Machines and for Uniformity of Hardness Standard Blocks

Class & Standard	Hardness range	Standard of testers			Standard of blocks		
		n	Standard value — Average value	Allowance of variation R	(n)	Tolerance of standard value	variation (R)
Rockwell standard for testers	>75 to ≦ 88 HRA	5	± 1.5	Refer to JIS ISO Standard	(5×2)	(± 0.6)	0.4
(JIS B 7726, ISO/DIS 6508)	>80 to ≦ 100 HRB	〃	± 2	〃	(〃)	(± 0.8)	1.0
Rockwell standard for blocks	20 to ≦ 70 HRC	〃	± 1.5	〃	(〃)	(± 0.6)	0.4
(JIS B 7730, ISO/DIS 6508)	HR 30N	〃	± 2	〃	(〃)	(± 1.0)	0.6
	HR 30T	〃	± 3	〃	(〃)	(± 1.3)	1.2
						VHS HS	
Shore standard for testers (JIS B 7727)	≧ 75 HS	10	± 1.5	2.0	10	(± 0.5) ± 0.6	1.5
Shore standard for blocks (JIS B 7731)	< 75 HS	〃	〃	1.5	〃	(〃) ± 0.4	1.2
Vickers standard for testers (JIS B 7725)	700 HMV						
Vickers standard for blocks (JIS B 7735)	0.2kgf	5	± 11%	8.0%	(3×2)	(± 5.3%)	4%
	1kgf	〃	± 5%	〃	(〃)	(± 2.5%)	〃
	700 HV						
	10kgf	〃	± 3%	4.0%	(5×2)	(± 1.0%)	2%
	30kgf	〃	± 2%	〃	(〃)	(〃)	〃
Brinell standard for testers (JIS B 7724)	<225 HB	3	± 3% ※	(8%)	(3×2)	± 2%	4%
Brinell standard for blocks (JIS B 7736)	≧225 HB	〃	〃 ※	(4%)	(〃)	± 1.3%	2%

1. Each value is based on JIS testers and blocks.
2. The values in parentheses are measured by our laboratory.
3. The tolerance of standard values should not over the above-mentioned values, due to our comparative testing results.
4. If the difference between standard, average values, and variations over each allowance, testers are needed to examine their accuracy.
5. ※The tolerance shall be ± 4% for the reading accuracy of 0,05mm. (See JISB 7724 5.6)

for daily inspection are summarized below.

(1) Before starting measurements, it is effective to conduct preliminary tests at one or more points outside the testing area on a block, especially for hardness tests that determine hardness values based on the depth of an indentation, such as Rockwell.

(2) The locations of test points should not be concentrated on a limited area of the block, but be evenly distributed over the test surface with a sufficient distance between indentations. This can be conveniently achieved by dividing the test surface into five sections as illustrated in Figure 6.

(3) First obtain the average $\overline{x}$ of the five-point measurements (x_1, x_2, x_3, x_4, x_5) from the equation

$$\overline{x} = (x_1 + x_2 + x_3 + x_4 + x_5)/5 \qquad (1)$$

and

(4) Calculate the error, which is defined as

$$\text{Error} = \ \overline{x} \ - \ \text{standard value of block} \qquad (2)$$

(5) Then calculate the range of variation R, which is defined as

$$R = x_{\max} - x_{\min} \qquad (3),$$

where $x_{\max}$ is the largest and $x_{\min}$ is the smallest of the five measurements.

(6) Confirm that the error and range of variation R obtained as described above are within the acceptable range as specified in the applicable standard for the tester tested, and record the result of the indirect verification. Table 3 shows tolerances specified in the standards for various hardness testers. If one wants stricter control than required by JIS, it is recommended to obtain $\overline{R}$ (average of R) by testing the block in advance and apply the $\overline{x}-R$ control chart method.

If strict control is desired, not only preliminary testing, but also testing the block after indirect verification is completed is recommended to confirm that the tester and the test itself have undergone no changes during the test. After use, the block should be repacked in rust-preventing wrapping and stored in a place away from heat and moisture.

4.4 Measures if the Results of Indirect Verification Are Not Within the Allowable Range

If the results of indirect verification are not within the allowable range specified in the applicable standard for the testing machine tested, reconfirm that no other elements of the factor are abnormal, and if necessary, ask the tester manufacturer or other specialist, such as a maintenance service provider, to conduct a direct verification of the tester. Before presenting a request, check the points that tend to be overlooked again: Inappropriate test load or objective lens is selected; and

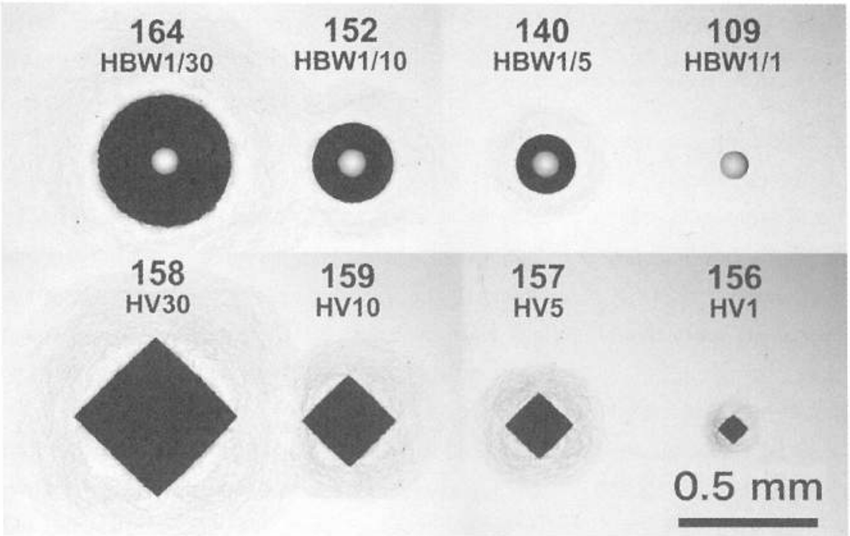

Fig. 7: Brinell and Vickers Indentations on a Hardness Block Made of Carbon Steel
The Brinell hardness values change significantly according to the test load applied.

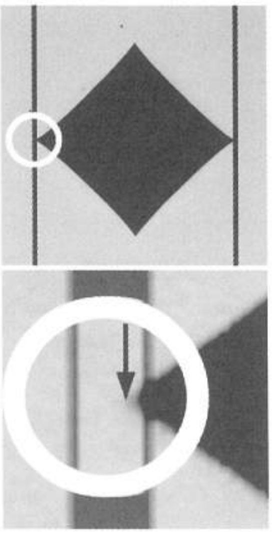

Fig 8: Marker Line Set Inward from the Angular Tip

the indenter is incorrect or damaged. If any problem is found through the direct verification, have the tester repaired and recalibrated, and conduct the indirect verification again using a standard hardness block.

4.5 Prohibited Actions when Using Standard Hardness Blocks

The following actions are prohibited when using standard hardness blocks for JIS-compliant indirect verification.

(1) Using a block whose warranty period has expired

(2) Using a block with too many indentations to ensure the specified distance between indentations

(3) Converting the hardness scale of the block

(4) Using the bottom face for testing or reprocessing the test surface

5. Points to Remember for Each Hardness Test Method

This section presents the points to remember when conducting daily inspections of a hardness tester using a standard hardness block for each of the popular hardness test methods.

5.1 Brinell Hardness

The biggest feature to remember of the Brinell hardness test is that the same hardness value cannot be obtained when the test is performed with different sizes of ball indenter or when different test forces applied because this test does not support the similarity rule of hardness.

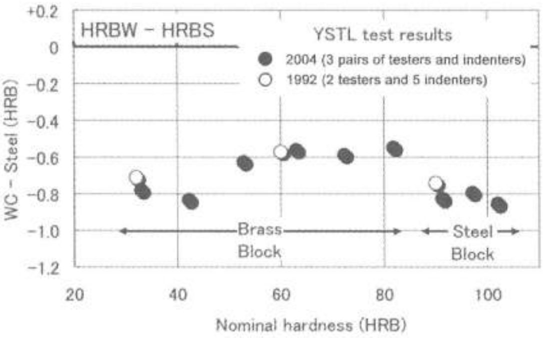

Fig. 9: Differences Between HRB Test Results for Steel and Cemented Carbide Ball Indenters

As shown in Figure 7, a hardness value varies with the test force applied, even if the same block is tested with the same indenter. As an exception, however, the hardness value becomes equal when the ratio of the test force to the square of the diameter of ball indenter is identical, such as HB10/3000 and HB5/750[7].

5.2 Vickers and Micro Vickers Hardness

Because the Vickers hardness test satisfies the similarity rule of hardness, the hardness value is constant regardless of the test force applied, as long as the test specimen is ideally homogenous (See Figure 7). Standard blocks for the Vickers and Micro Vickers hardness are applied for an extensive range of test loads. To serve their intended purpose, standard blocks need to carry two or three standard values for the large and small or large, medium and small test loads under which they are tested, as can be seen from Table 1. A request for testing the block under loads not given in Table 1 is also accepted if at all possible.

The Vickers test requires extra attention and experience when measuring the dimensions of an indentation. As shown in Figure 8, even if the marker line appears to be in contact with an angle of the projected indentation at its tip (upper photo), the marker may be set inward from the angular tip, making the tip invisible behind the marker (lower photo).

A request for making a so-called reference indentation is accepted because it is effective for setting conditions for the optical system of a microscope, confirming individual variability, and identifying the reason for the variability. However, it is not advisable to rely on the reference indentation as if it were a standard of length to calibrate the measurements of the diagonal length of indentations. The measuring microscope is supposed to be calibrated with a standard scale that has a higher definition than the indentations made by hardness testing. Centering light source and adjusting light intensity, aperture stop, and visibility of the eyepiece for measuring the dimensions of indentations according to each operator are more basic and important tasks than irresponsible corrections based on the reference indentation.

5.3 Knoop Hardness

The Knoop hardness test satisfies the similarity rule of hardness, as is the case with Vickers hardness. In addition, due to the shallowness of Knoop indentations, this test method enjoys entrenched popularity mainly in the United States. However, the Knoop method is generally limited to testing with micro loads, while the Vickers method covers an extensive range of test loads from large to micro.

JIS requires that the Knoop indenter be replaced by a Vickers indenter and a Micro Vickers test block be used to carry out indirect verification of a hardness testing machine for Knoop hardness. For testing the hardness of thin layers, for example, the nanoindentation hardness method is increasingly applied these days, as mentioned in Section 5.6.

5.4 Rockwell Hardness

For Rockwell scales using a ball indenter, such as HRB, the ASTM and ISO standards have been revised to allow the use of only a cemented carbide ball indenter. JIS is likely to be so revised in the future, but currently allows the use of a steel ball indenter, which is still the mainstream in Japan. Although the standard values on YSTL blocks for the HRB scale are indicated in HRBS, which shows the results of testing with a steel ball indenter, requests for additional testing with a cemented carbide ball indenter with the result shown in HRBW are accepted. The same applies to all Rockwell scales using a ball indenter, including HRT. Figure 9 shows differences between HRB test results for steel and cemented carbide ball indenters.[8)]

If a ball indenter applies too large a test force or is used forcibly to test hard materials, it might undergo permanent deformation. As a result, the deformed indenter will continue to generate inaccurate test results thereafter. What is worse, such deformation cannot be detected externally, so the only possibility of detecting it is through daily checks of a tester's accuracy using a standard hardness block. When a tester is shared by more than one operator, it is important to ensure that the status of the tester is shared among the operators.

5.5 Shore and Other Rebound Hardness

Rebound hardness test methods, including Shore, are especially subject to the mass and the status of the reverse face of a test specimen. Therefore, it is required that a Shore hardness block be tested on a JIS-specified testing machine frame. The longstanding support for Shore hardness in Japan is largely due to the efforts of testing machine-related parties and the success of the VHS conversion method developed by Dr. Takeo Yoshizawa, the first chairman of MTRAJ. With this conversion method, the results of Vickers hardness when testing a standard hardness block made of eutectoid carbon steel (See Figure 1) is converted into the corresponding value of Shore hardness, which then serves as the standard value for the block. JIS specifies the material of blocks available for such a purpose and the conversion formula as follows.

$$VHS=\left\{1.7435\left(\frac{HV}{1000}\right)-1.1505\left(\frac{HV}{1000}\right)^2 + 0.5818\left(\frac{HV}{1000}\right)^3-0.1609\left(\frac{HV}{1000}\right)^4\right\}\times 100 \qquad (4)$$

For Leeb hardness, large blocks developed by the Roll Hardness Committee of MTRAJ are available and their standard hardness values are available in HLD and HLE through conversion from Vickers hardness as specified by the committee.

5.6 Instrumented Indentation Test for Nanoindentation

The instrumented indentation test can evaluate various mechanical properties—including hardness—of a material based on the load-displacement curve while the test is being performed, even if the material is less able to hold residual indentations or microscopic measurement of the dimensions of an indentation is difficult to achieve. In Japan, due to its availability in the ultra-micro-load range, there are growing expectations for this method to be used for so-called nanoindentation.

The instrumented indentation method is different from the conventional hardness test methods in that it has some factors that require calibration, in addition to the load and displacement measuring systems of the tester. Such factors include the deviation of indenter tip geometry from its ideal state and the amount of elastic deformation of the tester and indenter. The tester must be calibrated for these factors as area function and frame compliance, respectively, using a standard specimen specified for that tester. This calibration can be considered to fall under the category of direct verification of conventional hardness testers. Therefore, the abovementioned standard specimen is different from the hardness block used for an indirect verification of a tester.

The standard blocks for nanoindentation supplied by YSTL include the UMV Series (UMV900, 700, 500 and 200) blocks made of polycrystalline metal, which are almost equivalent to Micro Vickers blocks, and the HN-W blocks made of single-crystal tungsten. For both blocks, the Vickers test results under a test force of 1 or 2 gf are shown, and for reference, the results of nanoindentation tests with a test force of 1 gf are provided in the form of hardness values and load-displacement curves (See Figure 1). One should keep in mind that nanoindentation tests are generally susceptible more to ambient environments, including temperature, vibration, and noise, and how the specimen is fixed, than conventional hardness testing methods.

6. Conclusions

Originally, hardness tests acquired their current popularity because they provided an easy, convenient, and highly reliable means of evaluating the strength of a material. It is satisfying to know that the efforts of MTRAJ and related parties have led to the development of excellent, advanced hardness testers and standard blocks and improvements to applicable industrial standards, which have contributed to the advancement of industrial and engineering studies.

Peripheral issues surrounding the matter of hardness tests, such as accreditation and uncertainties, cannot be neglected, but the focus of discussions should not stray from the essence of hardness. As specialists we are requested to provide a hardness-testing environment that is friendly to users of hardness testers. Otherwise we will lose their support. To achieve that, we need neither unnecessarily detailed provisions, fat books of standards that make one feel reluctant to read them, nor complicated and difficult calculation procedures. Rather, we need hardness test methods for which theory and applications have been carefully studied, along with the resulting development of highly sophisticated and user-friendly testing machines and highly accurate standard blocks that guarantee the appropriateness of such testers and testing procedures.

In this article, I present some views from the perspective of a manufacturer of standard hardness blocks on how blocks should perform, as well as a brief explanation on how these blocks should be used. If these can be of any service to the understanding and businesses of readers, I would be more than happy. A corporate philosophy reflected by the slogans—"pursuit of zero hardness dispersion" and "standard hardness blocks as a guarantee of accuracy"—upheld by YSTL's former presidents Shoichi and Hiroshi Yamamoto accurately represents the desired stance of a manufacturer of standard hardness blocks. We will make continued efforts to pursue this philosophy, and would like to ask for the continued support of MTRAJ. Finally, I would appreciate any opinions from the readers of this article not only about the discussions presented here but also on various other subjects that concern hardness.

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How to make a hardness test in the right way

Takashi Yamamoto

1. Introduction

At home we have two brother cats with long white coats, so there are white hairs everywhere in the house. Sometimes I wonder which cat is bigger, but it seems difficult to measure their body lengths accurately due to the soft, long hair covering their bodies. Perhaps it would be possible to make an accurate comparison by shaving off their fur and straightening their curved backs, but it would be pitiful to see the resulting appearance, and such a comparison would not be meaningful anyway. The same applies to the case of hardness testing where adhering too much to the accuracy of measurements might fail to achieve the originally intended purpose of testing[1), 2)].

As a manufacturer specializing in hardness reference blocks, we put greater emphasis on the accuracy of hardness testing procedures rather than seeking the accuracy of measurements obtained. When talking about the strength of a material, using two-digit numbers is the norm to show measurements of strength. Rather than just increasing the digits of average hardness measurements or resolution of the tester, what is more important when discussing the accuracy of hardness testing, I think, lies in a better understanding of the notion of hardness and the characteristics of different hardness test methods. Therefore, Section 2 presents a cross-sectional view of hardness test methods from several perspectives. Section 3 presents the typical characteristics and key points of major hardness test methods. Section 4 presents some basic matters that need attention. And, Section 5 introduces some new hardness testing methods that are under development.

2. Some Perspectives for Understanding Hardness Testing

The appearance of a mountain varies according to the direction from which it is viewed—whether from the north, south, east, or west, or looked down upon from an aircraft. Many different hardness test methods are available, but before going into the details of each method, a cross-sectional view of the different methods from several perspectives would help provide a better understand their different and common features.

2.1 Hardness as an industrial quantity

Hardness does not have a specific unit of measurement. We have a shared understanding about measures defined by *1 meter* and *1 gram,* but have never heard of a specific quantity defined by *1 hardness*. A value of hardness is the result of tests conducted under predefined conditions, and is called an industrial quantity. Many people who are well-versed in physics consider that a value of hardness is something obtained as the result of testing, rather than being something that is measured. In a dictionary, *testing* is defined as the activity of trying something to find out what it is. This, indeed, applies to the matter of hardness and hardness reference blocks. A hardness reference block is not a standard substance that serves as an absolute scale of hardness, but is only a secondary standard used for industrial purposes in that the block is only a test piece specially made to present extremely uniform values of hardness when tested in strict accordance with defined conditions. The absolute standards relied upon to determine the accuracy of hardness are the accuracy of the test force being applied, measurement of the dimensions of indentations made, and the definition of the testing cycle to be followed.

2. 2 Indentation Hardness and Rebound Hardness

Figure 1 shows a model of the curve of indentation depth (h) measurements when the test load (P) is being applied and removed in a hardness test cycle. The indentation hardness test method uses indentation depths along these curves or microscopic measurements of the dimensions of an indentation after removing the load to

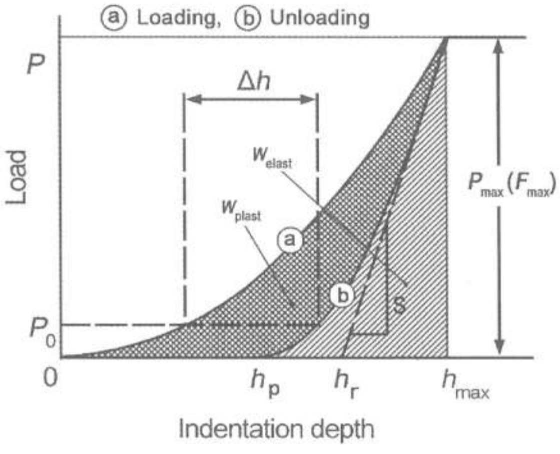

Fig. 1: The Test Load v.s. Indentation Depth Curve ($P - h$ Curve) as a graphic expression of the hardness test cycle

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define hardness. Many current hardness test methods are categorized as static indentation hardness test methods, which require several seconds to several tens of seconds to generate an indentation.

Meanwhile, the rebound hardness test method defines hardness as a change in the rebound motion of an indenter after it strikes a test sample—in other words, the kinetic energy of an indenter that has been consumed to generate an indentation. The softer the sample is, the larger the indentation is. This means the energy consumed for plastic deformation (W_{plast}) becomes larger, reducing the kinetic energy of the rebounded indenter accordingly, as illustrated in Figure 1. In a way, the rebound hardness test is a variety of indentation hardness tests conducted by instantaneously generating an indentation.

2.3 Projected and Surface Areas of an Indentation

Many indentation hardness test methods use force divided by area of indentation to determine values of hardness, as is the case when determining values of stress. For this reason, a lot of research has been conducted on the relationship between hardness and tensile strength and other physical properties. Currently, more test methods choose to use the surface area of an indentation than the projected one, but theoretically it is known that the projected area reflects the strength of the material more accurately3). However, this relates to the shape of an indenter discussed in Section 2.4, but choosing the surface area of an indentation to determine the value of hardness does not pose any problems if a pyramidal indenter is used, because the projected and surface areas of a ball indenter are not proportional to each other, but those of a pyramidal indenter are.

2.4 Similarity Rule of Hardness and Indenter Geometry

If a pyramidal or conical indenter is used, the cross-sections of the resulting indentation are similar, irrespective of the test load applied or the size of the indentation. This means that, in principle, a consistent shape of deformation, not a consistent *amount* of deformation, can be applied to a test material, regardless of the test load applied. Therefore, if the test sample is ideally homogeneous, the same value of hardness, or applied force divided by area of indentation, can be obtained, regardless of the test force applied. Compared to this, the cross-sections of an indentation made with a ball indenter differ with the test load applied. If the shape of a test sample deformation is inconsistent under different test loads, the values of hardness obtained become different. This is called the similarity rule of hardness. This rule applies to pyramidal and conical indenters, but not to a ball indenter, except in the special cases described in Section 3. 3.

It is also said that an indenter with an extremely sharp tip can cause friction between the sample and the indenter surface that affects the test results3). As described in the following section, the sharpness of the tip of a pyramidal or conical indenter becomes an important issue when it is used for test methods based on the penetration depth of an indenter.

2.5 Indentation Depth and Microscopic Measurements

It is generally recognized that determining the size of an indentation by measuring its depth is easier and produces fewer human errors than by measuring its area. Table 1 provides details of the Rockwell hardness test as a

Table 1: Principles of Rockwell Hardness Tests

Test Method		Scale	Method of Indentation Measurement	Definition of Hardness: Based on Depth (h)		Indenter			Conceptual Classification	Year of Invention
				Formula of Hardness Definition (Preliminary test force kgf / Total test force kgf)	Unit System when Invented	Material	Indenter Geometry	Shape of Indentation		
Hard metals, etc.	Rockwell	HRC, etc.	Indenter's penetration depth is measured: (1) Apply the preliminary test force to determine the origin of depth measurement. (2) Increase the load until it reaches the total test force. (3) Remove the load until it reaches the preliminary test force. Measure the difference in depths—h (mm)—at the test forces (1) and (3).	Hardness = 100 -500 h (10/150, etc.)	CGS	Diamond	Spherical tip R = 0.2 mm Cone angle = 120°	Not similar	Macro	1919
	Rockwell Superficial	HR30N, etc.		Hardness = 100 -1000 h (3/30, etc.)					Macro (Light load)	
Soft metals, etc.	Rockwell	HRB, etc.		Hardness = 130 -500 h (10/100, etc.)		Steel or Hard metal	Ball		Macro	
	Rockwell Superficial	HR30T, etc.		Hardness = 100 -1000 h (3/30, etc.)					Macro (Light load)	

typical depth-measuring method. There are two types of depth-measuring method. One uses the depth of an indentation directly to determine a value of hardness, such as the Rockwell hardness test. The other uses the area of an indentation estimated by measuring its depth, as exemplified by the instrumented indentation test that is applicable to nano-indentation. Measurements of indentation depth are subject to the elastic deformation of tester and indenter under a test load, or frame compliance in other words. The smaller the test load is, the more difficult it is to detect the surface of a test sample as the base point for measuring the indentation depth. In addition, the truncation of an indenter tip after repeated use leads to smaller depth measurements, widening the range of errors of hardness values. These problems must be addressed when using the depth-measuring method. This is why a triangular pyramid indenter, such as Bercovich, is used more often than a Vickers indenter for nano-indentation testing, because theoretically one only needs to polish the three sides of the pyramid to sharpen the tip of the triangular pyramid indenter.

Table 2 shows the hardness test methods with which the dimensions of an indentation are measured microscopically to determine its area, from which a hardness value is calculated. Although instrumented indentation testing does not actually involve microscopic measurements of an indentation's dimensions, it is included in Table 2 because it applies the method of calculating hardness using the area of an indentation. A hardness test method based on microscopic measurements requires some time and effort, which is more likely to invite human error. However, put simply, if a test load is applied correctly, the size of a resulting indentation will be consistent and not be subject to such problems as frame compliance and errors related to detecting the surface of the test sample. In addition, the projected area of an indentation reflects the strength of the test sample and is almost free from the influence of the indenter tip's truncation.

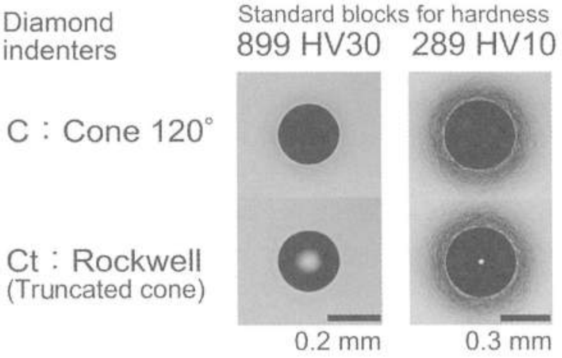

Fig. 2 Indentations on steel standard block by a conical diamond indenter with an angle of 120° and a Rockwell diamond indenter

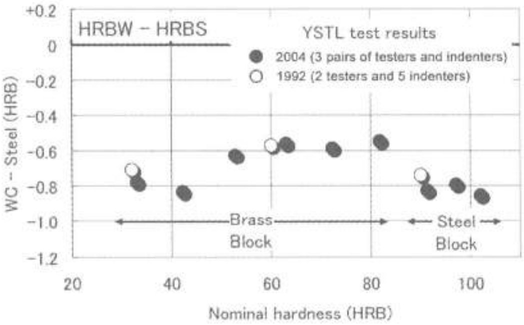

Fig. 3: Difference in HRB Test Results between Steel and Cemented Carbide Ball Indenters

Figure 2 shows an example comparing the two methods of determining the size of an indentation: area-measuring and depth-measuring. As can be seen from this photo, there is little difference in the projected area, or the diameter, of the indentation between a diamond cone indenter with a cone angle of 120° and a Rockwell diamond conical indenter with a spherical tip of R = 0.2 mm. On the other hand, the depth of an indentation under a test load is as much as 45% shallower on a 900 HV test block and 25% shallower on a 300HV block with the Rockwell diamond indenter[4]. This shows the higher reliability of the microscopic area-measuring method over the depth-measuring method. However, an optical measurement is harder to perform for smaller indentations. Therefore, at present, there is no choice but to use the depth-measuring method as adopted by nano-indentation testing for such a hardness range.

3 Features of Major Hardness Test Methods

Subsequent to the cross-sectional view of various hardness test methods presented in Section 2, this section provides the features and key points of each of the major hardness test methods individually.

3.1 Rockwell Hardness Test (JIS Z 2245)

The Rockwell hardness test determines hardness directly from measurements of the depths of indentations. This test method features relatively large test loads and simple testing procedures, and is useful for identifying subtle differences in hardness among different samples. However, it is difficult to find the theoretical significance of hardness values obtained by Rockwell testing. Because this test has as many as 30 hardness scales, from among which one should find the appropriate one according to the hardness or thickness of a test sample, if the sample is tested with all 30 Rockwell scales, the same hardness value cannot be obtained as the similarity rule of hardness does not apply to this test. In particular, the choice of scale becomes an issue when testing an unknown sample. In such a case, the test should be done first with a scale that is suitable for testing hard samples using a diamond indenter. If the sample is found to be too soft for the scale chosen and measures low on the scale, the person conducting the test should switch to another scale for softer materials using a ball indenter. Reversing this order can damage the indenters and testers.

Rockwell hardness testing uses differences in measurements of the depth of an indentation Δh under preliminary test force P_0 before and after the total test force P is applied. (The author calls Δh the differential depth.) Because the amounts of elastic deformation of the tester and the indenter under the preliminary test force do not differ whether they are measured before or after the total test force is applied, using the differential depth instead of the depth under the total test force can virtually nullify the effects of elastic deformation or frame compliance mentioned earlier. In addition, the base point for measuring the depth of an indentation is fixed by applying the preliminary test force, which eliminates the need to detect the surface of the test sample from which the depth of an indentation is measured, and reduces the effect of the truncation of an indenter tip. For these reasons, Rockwell hardness testing is an excellent method for industrial applications. Despite the fact that it defines hardness simply as "a constant minus the depth of an indentation and does not take into account the dimensions of hardness in the first place, the Rockwell method is used most extensively in the industrial world. This shows how convenience and reproducibility are important to achieve popularity among industrial users.

(1) Sample Surface and Anvil Surface

The most important point requiring care in Rockwell hardness testing is the accuracy of indentation depth measurement. Therefore, dirt, dust, rust, scratches, oil, or similar matter must not be present on the anvil of the tester on which a test sample is placed and the back sides of the sample and the hardness block. Greater attention should be placed to the rear sides, rather than the front ones[5]. Attention is also required for the faces exposed to the anvil or the indenter when they are inserted into the tester. In Vickers testing, a test sample is often embedded in resin, but this is not suitable for Rockwell testing, because the resin or how the sample is embedded may influence depth measurements.

(2) Rockwell Diamond Indenter

Suitable for testing a hard sample, such as heat treated steel, a Rockwell diamond indenter is a conical indenter with a cone angle of 120° and a spherical tip whose radius equals 0.2 mm. The spherical tip has the advantage of protecting the indenter against damage, but sphericity becomes a drawback because it disables application of the similarity rule of hardness and prevents a consistent hardness scale not subject to applied test load from being obtained.

(3)Ball Indenter: Shift to Cemented Carbide Ball

When testing soft materials, including nonferrous metals and mild steel, a steel ball or a cemented carbide

Table 2: Test Methods That Define Hardness Based on Area of Indentation

Test Method	Scale	Method of Indentation Measurement		Definition of Hardness: Hardness = Force / Area of Indentation			Indenter			Con-ceptual Classificati-on	Year of Invent-ion
		Depth Measured	Micro-scopic	Surface Area	Projected Area	Unit System when Invent-ed	Material	Indenter Geometry	Shape of Indent-ation		
Brinell	HB		● After load is removed	●		CGS	Hard metal (Steel)	Ball	Not similar	Macro	1900
Meyer					●						1908
Vickers	HV			●			Diamond	Square pyramid Angle between opposite faces: 136°	Similar	Macro Micro	1925
Knoop	HK				●			Quadrangular pyramid Angles between opposite edges: 172.5° and 130°		Micro	1939
Berkovich				●	(Note)			Pyramid Angle between indenter axis and faces: 65.03°		Micro	1951
Instrumented Indentation (Includes nanoindentation)	*HM* H_{IT}	● During load is being applied		●		SI		Berkovich, Vickers, Ball		Macro Micro Nano	ISO 14577 - 2002
					●						

Note: E. S. Berkovich defines both hardness based on the surface area of indentation (H) and hardness based on the projected area of indentation (H').

ball indenter is generally used. Testing using a ball indenter does not support the similarity rule of hardness. JIS allows either of these ball indenters, and using a steel ball indenter is currently the mainstream. However, ISO has made a complete switchover to the cemented carbide ball indenter. Due to differences in the elastic deformation of the two types of ball indenter, measurements of hardness when tested with a cemented carbide indenter tend to be lower than those obtained with a steel ball indenter, as shown in Figure 3 (The extent of the difference depends on the material tested). Therefore, taking the Rockwell B Scale as an example, the test results using a steel ball indenter are marked with HRBS, whereas those using a cemented carbide ball indenter are marked with HRBW to differentiate the test results according to which an indenter is used by adding the letter S or W to the hardness code HRB for the Rockwell B Scale.

Steel has lower Young's modulus and hardness and is weaker than cemented carbide. As a matter of course, if a steel ball indenter applies too large a test force or is used forcibly to test hard materials, it might undergo permanent deformation. As a result, the deformed indenter might continue to generate inaccurate test results thereafter without being noticed. The deformation of a ball indenter cannot be recognized from its outside appearance. This is one of the reasons why daily checking of a tester's accuracy via a hardness reference block is required. For reference, it is theoretically said that the strength of an indenter must be over 2.5 times that of the test sample[3)].

In general, the geometric accuracy of a ball indenter is very high. However, if the ball's support or cover becomes out of alignment with the central axis of the indenter, the ball would move while the test load is being applied, generating abnormal measurements of the depth of an indentation. The same error may also be caused if the ball cover is tightened excessively, which causes misalignment of the ball's center with the indenter axis. The ball cover must not be over-tightened so that the head of a ball projecting from the cover can roll smoothly under fingertip pressure.

3.2 Instrumented Indentation Test (ISO 14577)

The instrumented indentation test is another method for determining hardness based on measurements of indentation depth, but this method uses the area of an indentation estimated from the depth measured. With this innovative method, a computer takes in the measurements of the test load (P in Fig. 1) and the indenter's penetration depth (h) continuously during the process of loading, and analyzes the accumulated data to evaluate various properties of material strength, including not only hardness but also elastic modulus of indentation. Theoretically, this method is available extensively for macro- through nano-range testing[6)]. Generally, the instrumented indentation test requires testing a standard sample (not a hardness reference block), such as fused silica that has been specially prepared for each tester before starting the test. This is designed to correct for frame compliance and the indenter tip's truncation or area function—which is a function of the area A of an indentation based on its depth h to express the geometry of the indenter tip. Information on material strength obtained with this method includes Martens hardness HM and indentation hardness H_{IT} as shown in Table 2. The former hardness is calculated from the surface area of an indentation using the value of $h_{\max}$ shown in Figure 1, whereas the calculation of the latter hardness is somewhat complicated: obtaining the contact depth (h_c), which is indentation depth at a point slightly shifted toward the $h_{\max}$ side from h_r in Figure 1, and from the value of h_c, estimating the projected area of indentation at contact, from which the value of hardness is calculated.

Conventional hardness tests have difficulty obtaining measurable indentations on some test samples. For example, an indentation on a test material such as resin becomes hardly identifiable due to elastic recovery after the load is removed. It is also difficult to identify a residual indentation on a transparent sample such as glass. Sub-micron indentations on a thin film do not allow optical measurement. We can say that the instrumented indentation test is an innovative solution for these problems. Japanese hardness tester manufacturers had been intent on developing nano-indentation equipment from an early stage. There are excellent findings on corrections for frame compliance mentioned in Section 2.5 and the indenter's area function[7)]. Due to these efforts, the instrumented indentation test has been adopted as ISO 14577.

A big difference between the instrumented indentation test and conventional methods is that the accuracy of the test relies on correction using a standard sample. The conventional indentation methods may use a hardness reference block to confirm the appropriateness of a test, but the accuracy of the test basically relies on the force and length measured and no adjustment is required according to the strength properties of a standard substance.

Especially in the nano-indentation field of testing, the instrumented indentation test requires not only correction for the area function of the indenter tip, but also correct detection of the sample surface, appropriate fixation of the sample's reverse side, and careful measures to prevent external vibrations and changes to the sample and surrounding temperatures. If necessary, any erroneous detection of the sample surface is checked by reviewing test results.

3.3. Brinell Hardness Test (JIS Z 2243)

Brinell hardness testing is a highly reliable test method for determining hardness based on the surface area of an indentation that is calculated from the diameter of the indentation microscopically measured. Currently, this method only accepts use of a cemented carbide ball indenter (HBW), and is not usually applied for testing hard materials such as hardened steel or small pieces. This method is used for obtaining the average hardness of a relatively large sample, because it generally produces indentations that are as large as several millimeters in diameter. Because a ball indenter with a diameter of 10 millimeters and a test load of 3,000 kgf are frequently used for Brinell testing, Brinell hardness is sometimes shown without the hardness code that describes the testing conditions used: for example, Brinell hardness 300, instead of 300 HBW10/3000. In practice, however, many different combinations of indenter diameter and test load are used, and the value of hardness varies with the combination used because Brinell does not support the similarity rule of hardness. Therefore, as is required by JIS, a hardness value must be accompanied by the applicable hardness code such as 300 HBW10/3000.

There is another test method called Meyer Hardness, which also measures the diameter of an indentation and determines hardness based on the projected area of the indentation, which reflects the strength of the test piece. It is said that Meyer hardness is more rational than Brinell[3)], but the Brinell test method, which was invented earlier, enjoys an overwhelming prevalence even after the passage of one century since its invention.

The Brinell test does not generally support the similarity rule of hardness, but as an exceptional case, it supports the similarity rule of hardness, as long as $P/D^2 =$ Const., where P is the test load applied and D is the diameter of the ball indenter used, and the values of hardness obtained with this load-diameter combination can be regarded as equivalent. The P/D^2 ratio is important and often used, but it is not given a fixed designation. Should we call it the Brinell ratio to show respect for the inventor of the Brinell hardness test?

3.4 Vickers Hardness Test (JIS Z 2244)

The Vickers hardness test determines hardness based on the surface area of an indentation that is calculated from the microscopically measured diagonal length of the indentation. Because this method supports the similarity rule of hardness, a single hardness scale is sufficient to test various samples under different test loads, no matter how soft or hard they are, unlike the case of the Rockwell method. As shown in Figure 4, if the same indenter is used, the hardness values of the Brinell method vary with the test loads used, whereas those of the Vickers method remain almost the same under different test loads. It would be safe to say that any variance of Vickers hardness values tested with the same indenter is attributable to inclination or differences in hardness (or strength) in the depth direction of the test sample. Occasionally, erroneous test loads can cause such a variance, so it is important to confirm the accuracy of test loads by testing a standardized block under different test loads. Because the

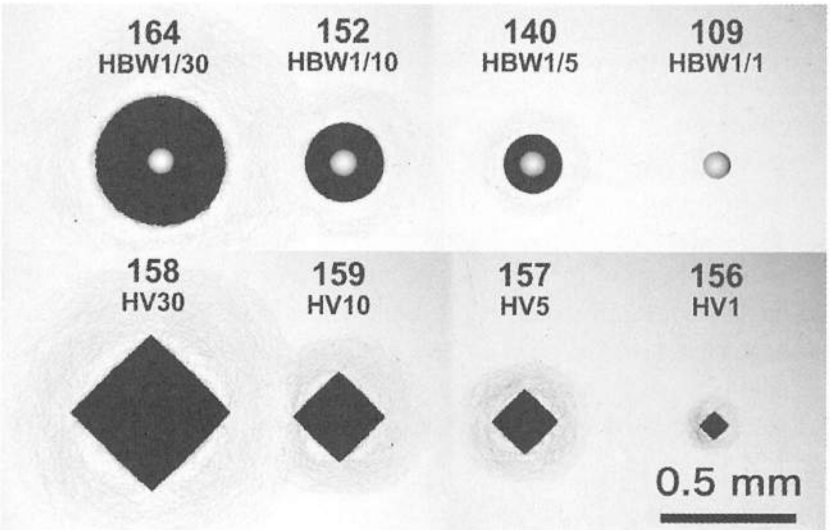

Fig. 4: Brinell and Vickers Indentations on a Hardness Reference Block Made of Carbon Steel

The Brinell hardness values change significantly according to the test load applied.

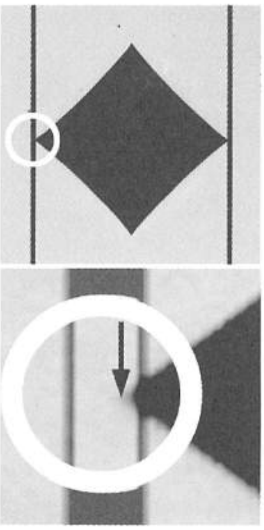

Fig. 5: Marker Line Set Inward from the Angular Tip

size of a test load used is important in relation to metallographic structure as discussed in Section 4.2, the hardness code of Vickers should also be accompanied with a number representing the test load used as in HV0.1. It is required that standardized blocks for Vickers and Micro Vickers hardness are tested under different loads.

Because the periphery of an indentation tends to lift or subside, the size of the indentation is usually difficult to measure. However, the Vickers method is based on the diagonal length of the square-shaped projection of an indentation, which is subject less to peripheral deformations[8].

The most vulnerable aspect of the Vickers method is measuring the diagonal length of an indentation. It is important to adjust the tester's visibility correctly to obtain the correct zero point. As shown in Figure 5, a beginner tends to set the marker line inward from the angular tip of a projected indentation, causing smaller measurements than actual values. What is worse, unlike the case when the indentation is over-measured, this error is likely to be left unnoticed, because the marker line looks perfectly aligned with the angular tip at first glance, as can be seen in the upper photo in Figure 5. To avoid such an error, a monitor and image-processing technique are currently used, but the basis of achieving correct measurements still lies in the accuracy of naked-eye sighting.

(1) Visibility Adjustment and Zero Point Confirmation

To the side of the eyepiece of a single-lens reflex camera there is a lever or dial for making adjustments in accordance with the viewer's visual acuity. Unless this is adjusted well to the user's eye, photographs taken become out of focus. Similarly, it is essential to adjust the eyepiece of a Vickers hardness tester for each operator to achieve correct measurements of the diagonal length of an indentation. This adjustment must be done for each operator before a test is conducted because the distance of distinct vision differs from operator to operator. Specifically, the microscope is set so that the mirror-finished surface of a test sample, such as a hardness reference block, comes into focus, and the distance between marker lines is narrowed. If the adjustment is not made correctly, the gap between the lines looks blurred. In this case the adjustment ring for the eyepiece is rotated until the gap can be seen with greatest clarity, as shown in Figure 6. Next, the distance between marker lines is narrowed further, and the same adjustment is repeated. Finally, if possible, the lines are narrowed until they are nearly in contact with each other, with a thread of light barely seen between the lines, and the same adjustment is repeated. When the adjustment is completed, the marker lines are made to overlap perfectly and the zero point is confirmed. If the aforementioned adjustment procedures are accomplished successfully, the counter (for measurement of the diagonal length) should indicate virtually zero.

We actually confirmed the importance of the visibility adjustment by having six operators at YSTL measure the

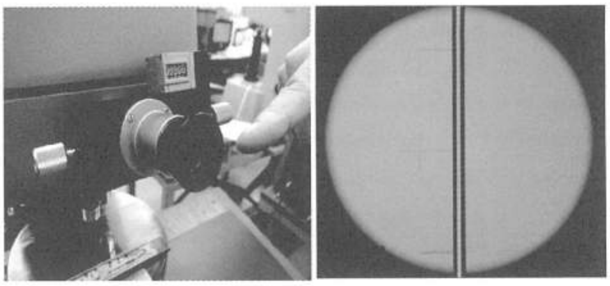

Fig. 6: Visibility Adjustment of the Objective Lens of a Vickers Tester (Left: Visibility Adjustment Ring, Right: Field of Vision After Adjustment)

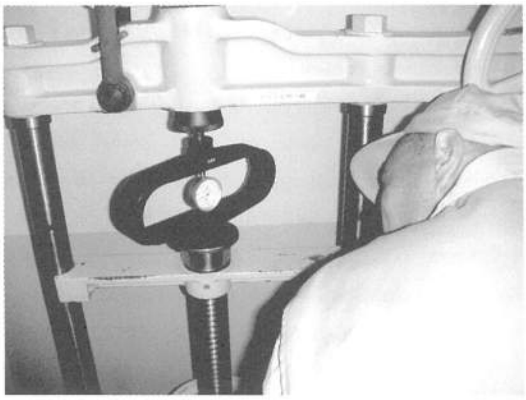

Fig. 7: Direct Verification of the Tester (Verification of the Test Load)

Table 3: The Scales and Nominal Hardness Values of JIS/ISO-Compliant Hardness Reference Blocks Available for Daily Inspection (Indirect Verification) of Testers

HR C	70,67,64,62,60
HR C	57,55,50,45,40,35,30,25,20,10
HR A	87,85,83,81,78,75,71,65,56
HR30N	83,81,78,73,67,60,55,50,41
HR15N(45N)	92,90,87,85,80,75(43)(23)
HR BS	100,95,90,82,72,62,52,42,32
★HRB	(HRB S+W) : d-HRB 90,62,32
HR30TS	78,72,62,52,42,38,32
HR15TS	87,82,78
HR E90,HR M 107,67,HR L 118,92,HR R 123,105,HRF 90,HRS 90	
HMV(1,0.1)	1650
HMV(1,0.1,0.01)	900,800,700,600,500,400,300,200,100,40
HMV(0.1,0.01,0.001)	30(Au)
HV(30,1)	1000,900,800,700
HV(10,1)	600,500,400,300,200,100,40
UMV(0.01,0.002)	900,700 (with Berkovich indentation 9.8 mN)
〃 (0.01,0.002)	500,200 (〃)
★HN-W	approx. 430 HV 0.001(made of single-crystal tungsten) (HV 0.01, 0.001 with Berkovich indentation 9.8 mN)
HS	100,95,90,80,70,60,50,40,30,20,7
HL	HLE(Dia) 850,800,700,600,500
HL	HLD(WC) 880,830,730,630,520
HBW(10/3000)	600,550,500,450,400,350
HBW(10/3000)	300,250,229(d=4mm),200,180,150
HBW(10/500)	125,100

diagonal length of an indentation made on a reference block for Vickers hardness once each after completing the above visibility adjustment procedures. The variance in the resulting measurements was much smaller than expected. At the hardness block manufacturer, YSTL, operators are well trained in adjusting for visual acuity and zero point confirmation and we do not make corrections for human errors by using so-called reference indentations.

(2) Influence of Diagonal Length Measurement Errors on Hardness Values

No matter how carefully one adjusts for visual acuity and zeroing, a certain range of measurement errors is inevitable. The influence of a measurement error in the diagonal length of an indentation on a hardness value is proportional to the percentage of the error to the diagonal length, not the absolute value thereof. Twice the diagonal length error percentage equals the percentage of a resulting error in Vickers hardness. Namely, a one-percent measurement error in the diagonal length of an indentation made on a 500HV test block will cause an error of 2%, or 10HV, in Vickers hardness.

3.5 Shore Hardness Test (JIS Z 2246)

The Shore hardness test is a rebound hardness test method that determines hardness by measuring the height of the rebound of a diamond indenter when it is dropped from a certain height onto a test sample. Because the Shore tester requires no power supply and is portable, it is suitable for testing large structures, such as mill rolls and railway rails, on the spot. The tester's stability when taking measurements is essential to obtain accurate results, because it uses the free fall of an indenter. The kinetic energy of the indenter for current rebound hardness test methods, including Shore, is relatively large. Therefore, when testing a thin or small test sample, the kinetic energy of the indenter is consumed as vibration energy, which causes errors in hardness values. This is called the mass effect of a sample. During testing, a thin or small test sample must be fixed onto a large surface plate.

The JIS B7731 standard for Shore hardness blocks specifies the use of conversion from Vickers hardness to determine the standard values of Shore test blocks. Due to the use of conversion, the block material is restricted to a specified type of steel. The higher popularity of the Shore test in Japan, compared to Western industries, stems largely from the successful adoption of this conversion method in Japan. Because the Shore tester is subject to the sample's mass effect, it is required to check the tester by testing an applicable reference block on the JIS-specified machine frame. As with Rockwell, careful attention is also required for the anvil and the reverse side of a test sample.

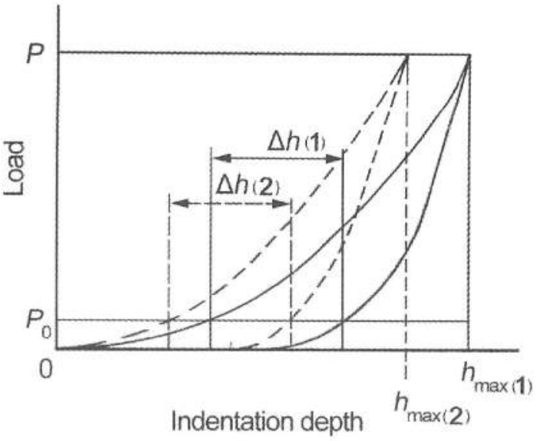

Fig. 9: Order of Hardness Between Different Samples Subject to Difference in Definition of Hardness

4 Correct Choice of Test Methods and General Points to Consider

To achieve accurate hardness tests, the accuracy of a hardness tester should be ensured first. In particular, it is important to secure the accuracy of the test loads and the dimensional measurements of indentations. As shown in Figure 7, verifying the tester's accuracy while measuring force and length—applied test forces and the dimensions of indentations—is called Direct Verification. It is strongly recommended that hardness testers receive direct verification by experts on a periodic basis, such as yearly.

Even if a tester is judged to be accurate as a result of direct verification, the tester and indenter can be damaged by repeated use. Daily inspection for such damage via direct verification is virtually impossible. Alternatively, a check can be made of the accuracy of hardness measurements obtained with a tester by testing hardness reference blocks as listed in Table 3. This is called Indirect Verification. Indirect verification using reference blocks is important not only to check the daily status of the tester and indenter, but also to check whether the tester is operated properly. For successful indirect verification, a test block manufacturer is required to produce test blocks that have extremely high hardness uniformity and provide highly reliable standard values of hardness.

The procedures for direct and indirect verifications are prescribed by JIS. There are some verification methods and hardness standard blocks that are not specified by JIS, but those methods and blocks are not generally acceptable.

4.1 Choosing a Test Method According to Size of Sample or Microstructure

The larger the test force applied is, the deeper the resulting indentation is, and the test result is subject more to the effects of the inner strength of the sample. In general, it is considered that the effects of deformation via indenter can reach a point about 10 times deeper than the indentation depth[3]. If that is the case, one might think shallower indentations are better, but every hardness test method tends to generate larger errors in test results when the test load is smaller, or the indentation is shallower. Accordingly, it is recommended that indentations should be as deep as possible, but do not exceed one tenth of the thickness of the test sample (or the surface layer or membrane of the sample for which hardness is measured). Specific guidelines for the appropriate depth (h) of indentations for each hardness test method are given below.

(1) Vickers hardness: $h=d/7$, where d is the diagonal length of indentation

(2) Brinell hardness: $h= P/\pi \times D\times$ hardness value (mm), where P is the test load (kgf) and D is the diameter of indenter (mm)

(3) HRC hardness: $h = 2$ (100 – hardness value) (μm)

(4) HRB hardness: $h = 2$ (130 – hardness value) (μm)

(5) Rockwell Superficial hardness: h=100 – hardness value (μm)

(6) Shore hardness: approximately 13-70(μm)

4.2 Structures To Be Tested

Especially when testing the hardness of metallic materials, consideration should be given to the microstructures to be tested and the depth of indentations when choosing the test method and loads applied. For example, if one wants to know the average hardness of a steel material that has a ferrite-perlite structure—a representative duplex structure of steel, one should choose the Brinell or Rockwell method. If one wants to find the difference in hardness between different structures, one should choose the Vickers method. The perlite structure is composed of layers of soft ferrite and hard cementite. To identify differences in the hardness of these constituent structures, Micro Vickers or nano indentation tests would be required.

4.3 Distance between Indentations

The distance between indentations is another important point to consider when making hardness tests. Because the circumference of an indentation is usually work-hardened, a distance of three to four times the diameter (or diagonal length) of an indentation must be ensured between the centers of adjacent indentations. The distance between the periphery of the test sample and the center of any indentation thereon must exceed 2.5 times the diameter (or diagonal length) of the indentation. From among the Vickers indentations shown in Figure 4, the hardness value obtained from the second indentation from the left appears to be higher. This suggests the possible effects of work hardening due to the larger indentation on the left.

4.4 Shapes of Test Sample

If one chooses the large-load Brinell or Rockwell hardness method to test the end face of a small-diameter test sample or the cross-section of a thin-walled pipe, or one chooses the Shore method to test the hardness of a thin material, the resulting test results could only be erroneous. Extra care should be taken when testing a sample that is tall and unstable or considerably overruns the anvil, or the tester or indenter might be destroyed. When testing these unusually shaped samples, the tester manufacturer should be asked whether it provides special jigs that aid the testing of such samples.

4.5 Hardness Conversion Table

When comparing the results of testing various materials with different hardness methods, the order of hardness can differ slightly between methods. This is due to the difference in how hardness is defined. For example, as shown in Figure 9, when comparing two materials that have the same differential depth (Δh), but differ in the depth of indentation under total test load ($h_{\max}$), the order of hardness of the two materials would vary according to which value of hardness is compared, whether the Rockwell value is obtained from Δh or the Martens value is obtained from $h_{\max}$. Although I often refer to the table of hardness conversion due to the nature of my business, I would use such a table only as a guide, without relying too much on the conversion to get data.

4.6 Contrasting the Projected Image of an Indentation

Although this is a minute point to consider, the contrast of the projected image of an indentation is subject slightly to the optical and lighting systems of the microscope used, because indentations are three-dimensional. Most microscopes use an incident illumination system, with which rays of light incident on the sample surface are nearly parallel to the optical axis. The reflected light from the sample surface goes straight into the objective lens, but the rays of light reflected from the indentation are inclined according to the contour of the indented surface. The higher the resolution of the objective lens is, or the larger its aperture angle and higher its numerical aperture (NA) are, the more rays of inclined reflection light from the indentation enter the objective lens. This makes the inner side of the projected indentation looks brighter, resulting in less contrast in the projected image of the indentation. This can lead to a failure to identify the border between an indentation and the surrounding surface of the test sample. The same kind of problem can occur due to the brightness of illumination or adjustment of the aperture stop. It is ironic that higher resolution lenses result in less contrast of indentations. If one is not sure about the measurement of the diagonal length of an indentation, it is recommended to try adjusting the brightness of the illumination or the aperture stop to increase contrast[9].

5 Development of New Hardness Test Methods

Based on a review of the characteristics of the existing hardness tests mentioned above, two new methods of hardness testing have been developed. Both methods have undergone basic verification tests, and await the development of hardness testers specialized for these methods.

5.1 Equivalent Indentation Depth Test

The conventional indentation hardness tests discussed in Section 3 have both good and bad points. For example, the instrumented indentation method is a useful unified method for evaluating hardness that covers all ranges from macro to nano. In fact, however, the method is found to require correction for frame compliance in the macro range, and to face such issues as difficulty of accurately detecting the true sample surface and the correction required for the area function of an indenter tip in the nano range. This somewhat complicates the management of testing conditions for an instrumented indentation test. The ISO requirements in this regard seem to be less practical in some regards. Based on a review of the characteristics of the instrumented indentation, Vickers, Rockwell, and other test methods have developed the equivalent indentation depth test as a method for solving the drawbacks of these tests from an industrial viewpoint.

The equivalent indentation depth test uses a pyramidal indenter, such as that used for Vickers testing, and the differential depth of indentations at the preliminary test force P_0. As an index of differential depth not subject to the amount of total test force P, the equivalent indentation depth is defined as $\Delta h_e = \Delta h / \sqrt{P}$. Namely, this method is designed to provide a single hardness scale for unifying all hardness tests in the macro to nano range by introducing the similarity rule of hardness into Rockwell hardness testing. Currently, efforts are being made to enable practical application of this method [4), 10)].

5.2 (Tentatively Called) Micro Rebound Hardness Test

Conventional rebound hardness tests are subject to the mass effect of the test sample as mentioned in Section 5.2, with some difficulties in testing small test samples. However, using a ball of several millimeters or less in diameter as an indenter for rebound hardness testing would make it possible to test smaller and thinner samples than usual. Moreover, if such ball indenters are treated as consumables, they can be used for instantaneously testing a red-hot sample at a high temperature or an extremely cold sample. Practical application of this hardness test could considerably extend the lower and higher ends of the sample temperature at which hardness tests can be conducted[11)].

6 Conclusions

I often hear that the definition of hardness is vague. I think this may be partly because we try to contain various qualities—some of which are hardly definable—of material strength in the limited word frame of *hardness*. Let us take the hardness of food for example. If we try to compare the hardness of *senbei* (a rice cracker) and a banana, we find that the quality or meaning of hardness differs between the two. The same applies to industrial materials. When people mention the hardness of rubber and metallic materials, they should actually be discussing their different qualities of hardness. The word *hardness* might have unexpected deeper meanings, and its definition may still need to be improved. Conversely, if we can supply a clearer and stricter definition of hardness, the testing of hardness will be able to reflect various aspects of hardness more accurately.

Meanwhile, I find growing attention being given to uncertainties and traceability in the industrial world. These factors may serve to indicate the excellence of Japan's industrial technologies, but attention to such issues alone cannot give birth to useful technologies. I also find that some of the standards for hardness testing some seemingly meaningless requirements. Experts on hardness testing should reacquaint themselves with the trends of industrial standards for hardness, but at the same time, they should always concentrate on identifying how they can maximize the effects of hardness tests and provide optimal environments where easy-to-use and highly reliable hardness tests are effectively used. Finally, let me extend my gratitude to the Japan Society for Precision Engineering and the New Hardness Tests task group of the Material Testing Research Association of Japan (MTRAJ, former Hardness Study Group) who helped me complete this article.

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HR C	57,55,**50**,45,**40**,35,30,25,20,10
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HR30N	83,**81**,78,73,**67**,60,55,50,41
HR15N(45N)	92,**90**,87,85,**80**,75(43)(23)
HRB S	100,95,**90**,82,72,**62**,52,**42**,32
★HRB Dual(HRB S+W) : d-HRB	**90**,82,72,**62**,32
HR30T S	78,72,62,**52**,42,38,32
HR15T S	87,82,**78**
HRE **90**,HRM 107,67,HRL 118,92,HRR 123,**105**,HRF 90,HRS 90	
HMV(1,0.1)	1600
HMV(1,0.1,0.01)	900,800,**700**,600,**500**,400,300,**200**,100,40
HMV(0.1,0.01,0.001)	30(Au)
HV(30,1)	1000,900,800,**700**
HV(10,1)	600,**500**,400,300,**200**,150,100,40
UMV(0.01,0.002)	900,700,500,200 (Berkovich 9.8mN tested)
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HLD(WC)	880,830,730,630,520
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HBW(10/3000)	300,250,229(d=4mm),**200**,180,150
HBW(10/500)	125,100

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S45C	S20C	SKS93	SNCM420
SK105	S30C	SKD11	SCr440
SKS2	S35C	SKD4	SCr420
SKD11	S40C	SKD61	SCM440
SKD61	S45C	SKT4	SCM415
SKH55	S50C	SKH2	SUS410
SUJ2	S55C	SKH4	SUS420J2
SCM440	SK85	SKH51	SUS430
SCM415	SK105	SKH55	SUS304
SUS420J2	S10C(Carburized)	SKH57	SUS316
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