

IMEKO 2010 TC3, TC5 and TC22 Conferences
 Metrology in Modern Context
 November 22–25, 2010, Pattaya, Chonburi, Thailand

RESEARCH OF NEW INDUSTRIAL HARDNESS TESTING USING “EQUIVALENT INDENTATION DEPTH Δh_e ”

*Takashi Yamamoto and Masayuki Yamamoto*¹, *Kensuke Miyahara*²

¹Yamamoto Scientific Tool Laboratory Co., Ltd.

²National Institute for Materials Science

1. THE PRESENT SITUATION AND PROBLEMS RELATED TO INDUSTRIAL HARDNESS TESTS

Hardness tests can be divided into two types according to the purpose for which they are applied: academic hardness tests which are mostly conducted in laboratories to evaluate the intrinsic strengths of materials; and, industrial hardness tests for controlling the quality of industrial products and their production processes. Hardness tests can also be categorized according to the principle of the testing method into static indentation, repulsive, and scratch hardness tests. Among the most popular static indentation tests alone, there are many different scales that define hardness, including 31 scales of Rockwell (HRA to Y and HR30Tm), and 21 scales of Brinell, Vickers, Knoop, and instrumented indentation (HM , H_{IT}). However, no scales

have a particular unit of measurement that directly defines the amount of hardness itself. Instead, a test force applied to cause a deformation in a specimen and the amount of deformation or depth of an indentation, constitutes the basis for determining hardness. Because there is no reasonable conversion relationship among the results of different hardness tests, today’s diversity of hardness scales might cause confusion in hardness testing. The instrumented indentation test, which is usually used for measuring nanoindentation hardness at laboratories, is not yet popular for industrial applications, because it requires complicated calibration procedures and sufficient knowledge and skills to perform the test. The equivalent indentation depth hardness test was developed as a hardness testing method that covers an extensive load range from macro to nano with a single hardness scale, unlike conventional hardness testing methods. This report discusses the benefits of this hardness test for industrial applications.

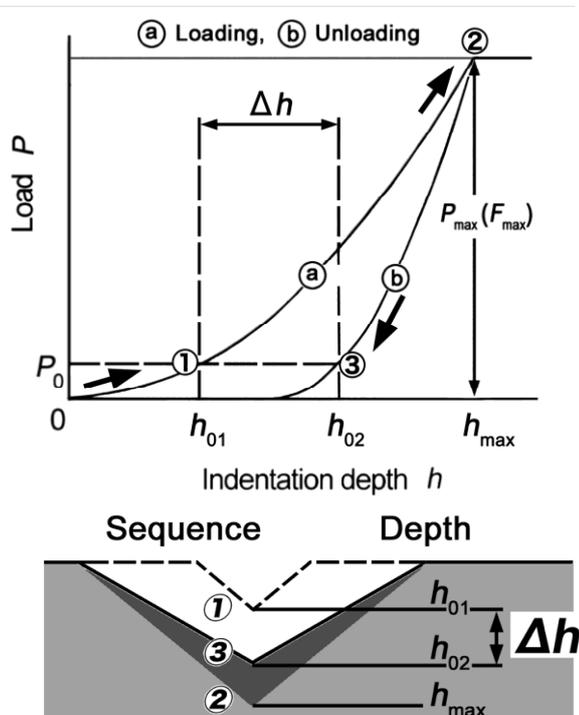


Fig. 1 Schematic drawing of differential depth Δh and indentation depth h of indenter.

2. PRINCIPLES OF EQUIVALENT INDENTATION DEPTH HARDNESS TEST

The equivalent indentation depth hardness test was developed for industrial use to achieve the following.

(1) **Consistency of Scale:** Unlike Brinell and Rockwell hardness, equivalent indentation depth hardness is designed to satisfy the similarity rule of hardness. Therefore, the value of hardness obtained with this test remains unchanged even if the test force applied varies according to the hardness and thickness of a specimen.

(2) **Measuring the Depth of an Indentation:** Unlike Vickers and Knoop hardness, the equivalent indentation depth hardness test is designed to use the depth of an indentation to determine the dimensions of the indentation. This makes the test easier to perform and available for nano hardness measurements beyond the resolution of an optical microscope.

(3) **Calibration Not Required:** Unlike the instrumented indentation test, the equivalent indentation depth hardness test is designed not to require difficult and complicated calibration procedures using a standard specimen, which can be a source of errors, and is, therefore, suitable for industrial applications.

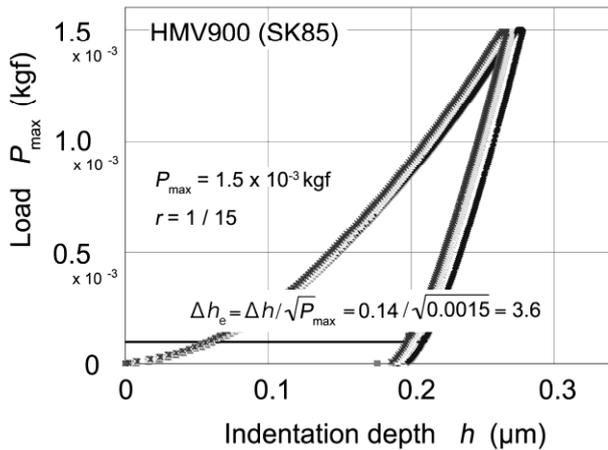


Fig. 2 Example of calculating equivalent indentation depth Δh_e in the case of nanoindentation.

Developed to attain the above purposes, the equivalent indentation depth hardness test features the following principles.

- (a) To satisfy the similarity rule of hardness, the test uses pyramidal diamond indenters, including Vickers and Berkovich indenters. (Consistency of Scale)
- (b) To avoid the process of compensating for differences in rigidity among individual testing machines and indenters, the test adopts the differential depth Δh as defined in Fig. 1 as a measure of indentation depth, which is the case with the Rockwell hardness test. (Measuring the Depth of an Indentation, Calibration Not Required)
- (c) The shape of an indentation obtained with the aforementioned testing methods is similar under different test forces applied, and measurements of indentation depth are proportional to the square root of the test force applied. The following equation (1) shows that the equivalent indentation depth Δh_e can be obtained by dividing the differential depth Δh by the square root of the total test force P_{max} .

$$\Delta h_e = \Delta h / \sqrt{P_{max}} \quad (1)$$

Following these principles, a hardness block of about 900 HV (made of SK85) was tested with the load ratio r of $P_0 / P_{max} = 1/15$. As a result, the equivalent indentation depth (Δh_e) under the total test force of 150 kgf (P_{max}) was calculated to be 3.7, for which kgf was used as the unit of force and μm as the unit of depth. Under one third of this test force, namely $P_{max} = 45$ kgf, the equivalent indentation depth came to the same value. This agreement under different test forces is something you cannot expect with the conventional Rockwell hardness. Even when the test force was reduced to 1/100,000, namely $P_{max} = 1.5$ gf, Δh_e was calculated to be 3.6, showing no significant difference from the two other results (Fig. 2). From these results, this hardness test is expected to be a method that provides a single hardness scale for an extensive range of test forces.

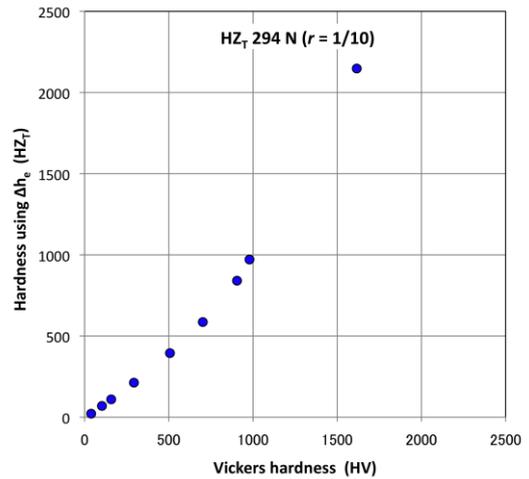


Fig. 3 Relationship between HV and HZ_T (tentative) hardness of Vickers standard blocks.

3. DEFINITION OF HARDNESS HZ_T BASED ON EQUIVALENT INDENTATION DEPTH Δh_e

As described above, there are high expectations that the concept of equivalent indentation depth will enable the establishment of a new industrial hardness test method for hardness measurements from the nano to macro range. However, the equivalent indentation depth Δh_e itself only serves as an index of indentation depth, or the softness of a material. To make the method available as a hardness test, a definition of the calculation formula for deriving a hardness value from Δh_e is required.

As reported earlier, the authors have accumulated results with the equivalent indentation depth test for a large number of high-accuracy Vickers and Micro Vickers hardness blocks over an extensive load range from macro to nano^{1)~4)}. From among these results, the results of Δh_e under total test force $P_{max} = 30$ kgf and preliminary test force $P_0 = 3$ kgf ($P_{max} = 294$ N, $P_0 = 2.94$ N, load ratio $r = 1/10$) were used to calculate a new hardness value HZ_T (Zaishikyo hardness, Tentative). For the calculation of equivalent indentation depth Δh_e , the units of kgf and μm were used for test force and indentation depth, respectively, in previous reports of the authors. Considering, however, that ISO standards require the use of N as the unit of test force for all hardness tests, the results of Δh_e were recalculated using the units of N and mm, instead of kgf and μm , before deriving the hardness value HZ_T .

The equivalent indentation depth hardness HZ_T was defined by equation (2), in which the hardness value is inversely proportional to the square of equivalent indentation depth, and Δh_e^{-2} is multiplied by a coefficient of 0.001 so that the digit number of the HZ_T hardness values almost agrees with that of Vickers hardness values.

$$HZ_T = 0.001 / \Delta h_e^2 \quad (2) \dots \text{Tentative definition}$$

Table 1 Vickers hardness HV and newly proposed hardness HZ_T based on equivalent indentation depth Δh_e at $P_{max} = 294$ N and $r = 1/10$ of Vickers standard blocks

HV	Tensile strength σ_B (MPa)	Δh (μm)	Equivalent indentation depth Δh_e and hardness HZ_T (tentative)		
			Δh_e by kgf and μm unit	Δh_e by N and mm unit $HZ_T = 0.001 / \Delta h_e^2$	
1616	—	11.7	2.1	0.000682	2148
979	—	17.4	3.2	0.00101	971
905	—	18.7	3.4	0.00109	841
702	—	22.4	4.1	0.00131	586
507	1734	27.3	5.0	0.00159	394
293	930	37.2	6.8	0.00217	212
158	515	51.8	9.5	0.00302	110
103	—	65.2	11.9	0.00380	69.2
39	—	117	21.4	0.00682	21.5

Notice: Values of tensile strength are obtained from SAE hardness conversion table for steel

Table 1 shows the HV (Vickers) and HZ_T (Equivalent Indentation Depth) hardness values obtained by testing HV blocks. For reference, the table also includes values of tensile strength converted from HV values according to the SAE J 417 conversion table for steel materials. Fig. 3 and Fig. 4 show the relationships among the three: HZ_T (Equivalent Indentation Depth), HV (Vickers) and tensile strength σ_B . Except for the Si_3N_4 ceramic material, the values of HZ_T hardness based on the equivalent indentation depth Δh_e have a good correlation with the values of σ_B and HV. This proves that the newly proposed HZ_T hardness can serve as a measure of material strength, as is the case with the Vickers hardness.

4. BENEFITS OF EQUIVALENT INDENTATION DEPTH ΔH_E FOR INDUSTRIAL USE

The aforementioned principles and features of the equivalent indentation depth test are expected to generate the benefits given below and in Table 2, if the test is established for industrial use as the HZ hardness test.

(1) Unlike Brinell, Rockwell, and Vickers hardness, the HZ hardness test based on equivalent indentation depth would be available for hardness measurements even in the nano range.

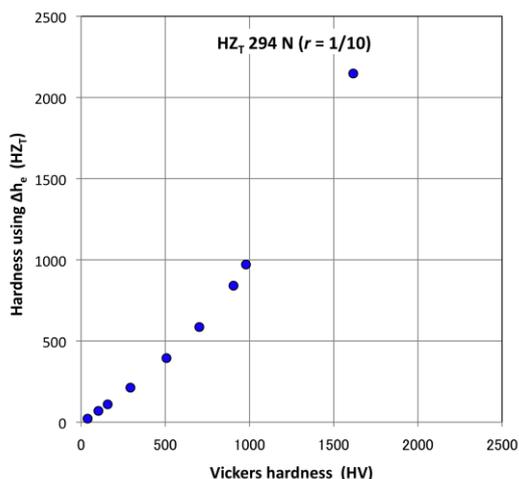


Fig. 3 Relationship between HV and HZ_T (tentative) hardness of Vickers standard blocks.

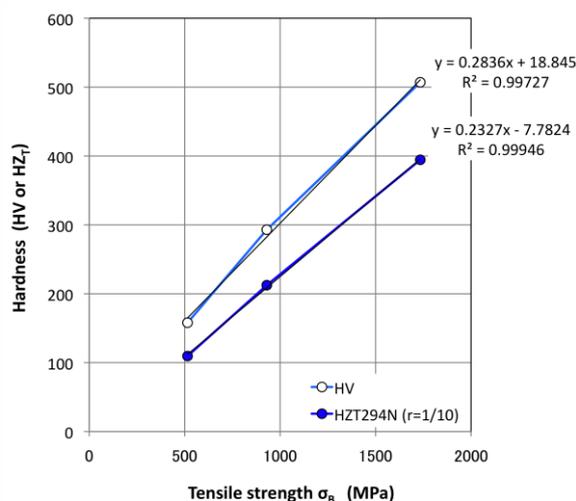


Fig. 4 Relationship of tensile strength obtained from SAE conversion table and HV and HZ_T hardness of Vickers standard blocks.

Table 2 Characteristics of industrial hardness testing methods

Hardness Test Methods	Satisfies Similarity	Needs no compliance correction	Needs no Surface detection	Applicable to Nano-indentation	Easy to use
Brinell		✓	✓		✓
Vickers	✓	✓	✓		
Rockwell		✓	✓		✓
Instrumented indentation	✓			✓	
Equivalent indentation depth	✓	✓	✓	✓	✓

(2) Unlike Brinell and Rockwell tests, which are subdivided into many different scales, the HZ hardness test based on equivalent indentation depth requires only a single scale to obtain hardness values over an extensive load range from macro to nano, because it satisfies the similarity rule of hardness.

(3) Unlike the instrumented indentation test for nanoindentation hardness, the HZ hardness test based on equivalent indentation depth requires neither detection of the true contact surface nor calibration using a standard specimen for compliance errors attributable to a testing machine and indenter.

(4) While the instrumented indentation test uses depth from the point where the indenter comes into contact with the surface of the specimen, the HZ hardness test based on equivalent indentation depth uses differential depth, which is less subject to the influence of indenter tip truncation. If the differential depth is more than six times larger than the amount of truncation, the test is almost free from such an influence.

(5) If the HZ hardness test is carried out in the macro or micro load range using a Vickers diamond indenter, you can obtain not only HZ hardness values based on equivalent indentation depth, but also Vickers (HV) hardness values by measuring the diagonal length of an indentation left on the specimen's surface.

Because equivalent indentation depth is based on the measurement of differential depth, the HZ hardness test

would basically be suitable for industrial use, rather than academic applications, as a measure of material strength. considering the industrial significance of its ability to provide a single hardness scale that covers an extensive load range from nano to macro, it would be meaningful to establish the equivalent indentation depth method as the HZ hardness test for industrial use. To this end, the authors will gather data and opinions from the broadest range of sources possible.

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