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PROOF EXAMINATION ON SMALL REBOUND HARDNESS CARRIED OUT WITH HLD/HLE STANDARD BLOCKS

M. Yamamoto [1], *T.Yamamoto* [1] ,*K. Miyahara* [2], *S. Maki* [3], *M.Nakamura* [4]

[1] Yamamoto Scientific Tool Laboratory Co., Ltd., Chiba, Japan, 2-15-4 Sakae-cho Funabashi 273-0038
[2] National Institute of Materials Science, Ibaraki, Japan, 1-2-1 Sengen Tsukuba 305-0047
[3] Mie University, Mie, Japan, 1577 Kurimamachiya-cho Tsu 514-8507
[4] Chiba University, Chiba, Japan, 1-33 Yayoi-cho Inage Ward Chiba 263-8522

Abstract: Conventional rebound hardness tests like Shore and Leeb hardness tests are mainly applied for massive and large specimens like mill roll. For small or thin specimens, however, "mass effect," i.e., loss of impact energy due to vibration of specimens during impact cannot be ignored. Nakamura and Maki proposed a simple rebound hardness test using a small ball indenter that is expected to reduce the mass effect.

In this paper, we developed a prototype of a free-fall-type rebound hardness tester and carried out experiments to provide fundamental information necessary to establish Nakamura-Maki method industrially.

Impact velocity and rebound velocity of ball indenters are estimated from free-fall height and rebound height, respectively. Experimental parameters are impact velocity, size, and materials of ball indenters. The most important result obtained is that coefficient of restitution, i.e., rebound hardness, is almost independent of the size of ball indenters and the rebound hardness scale can be set once other experimental parameters were fixed. Further study will be necessary to optimize experimental conditions and to measure accurate impact and rebound velocities in order to realize a versatile tester based on Nakamura-Maki method.

Keywords: Rebound hardness, Shore hardness, Leeb hardness, Coefficient of restitution, Impact velocity, Standard block for hardness.

1. INTRODUCTION

Rebound hardness testing, typified by the Shore hardness and Leeb hardness tests, is widely used as an on-site testing method for evaluating strength and deterioration diagnosis in large mechanical components such as mill rolls. In particular, in Japan the VHS conversion method based on Vickers hardness, which was developed by Prof. Takeo Yoshizawa, has become a JIS standard, and Shore hardness has enjoyed an extremely rare success worldwide, which continues to this day.[1), 2)] In the West, in the absence of the VHS method or other equivalent excellent management system, in the 1970s the new Leeb rebound hardness test gained ground, and a number of different scales are used with this testing method.[3)]

To determine the hardness, Shore hardness measures the rebound height of a freely falling indenter dropped from a fixed height, and Leeb hardness measures the ratio of the velocities of the indenter immediately before and after impact on the test piece, but if the effects of factors such as air resistance can be ignored, then the rebound velocity and rebound height of the indenter are the most significant factors, so that both of these use the rebound hardness principle. In these conventional rebound hardness tests, since the momentum and kinetic energy are large, when the indenter impacts the test piece, if the test is applied not to a large test piece of sufficient mass, then kinetic energy will be lost to vibration of the test piece, and the rebound speed or height will be reduced (the "mass effect" of the test piece). In such cases a correct hardness value will not be obtained. Furthermore, since there is no theoretical equivalence among the various derived scales for hardness measurement values, conversions have to be carried out by empirical correlation among experimentally obtained values.

On the other hand, the rebound hardness test advocated by Nakamura, Maki, *et al*, using a hard ball indenter (referred to as the "HNM method"), allows a high degree of freedom in the mass and emission velocity of the ball indenter, and thus accurate hardness measurement not only of large test pieces, but also of very small test pieces for which conventional rebound hardness testing is impracticable. The definition of this testing method is considered to allow the introduction of a rebound hardness scale which does not depend on the magnitude of the kinetic energy of the indenter.[4), 5)]

With the objective of introducing industrial hardness testing based on the principle of the HNM method, in this paper we describe the results of a demonstration experiment on rebound hardness testing using a free-fall hard ball indenter, to establish the industrial value of this principle.

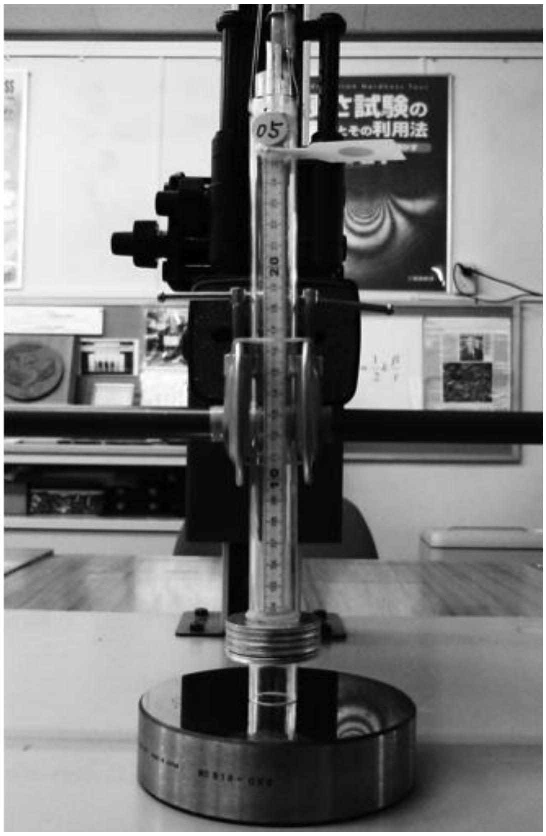

Fig. 1 Equipment used for h_1 = 25 cm

2. EXPERIMENTAL METHOD

2.1 Definition of coefficient of restitution

In hardness testing by the HNM method, the coefficient of restitution e is defined as ratio of the velocity V_1 of the hard ball used as an indenter immediately before impacting the test piece to the velocity V_2 immediately after. In this paper too, we define the coefficient of restitution by Equation (1).

$$e = V_2 / V_1 \qquad (1)$$

Here, V_1 and V_2 are the velocities (m/s) of the hard ball indenter immediately before and after impacting the test piece.

2.2 Hard ball used as indenter

It is essential for an industrial hardness testing method for metal materials to be able to assess the hardness not only of a metal material normal structure or machined structure, but also at least up to hardened steel. According to Nakamura *et al.* it is recommended that the hardball indenter should be at least 1.5 times harder than the test piece.[4] In view of this, for the hard balls used as the indenter, principally a cemented carbide ball such as the those that have been used successfully in Rockwell, Brinell, and Leeb hardness testing was used, and for purposes of comparison a steel bearing ball, alumina ceramic ball, and silicon nitride ceramic ball were also used. The material, diameter, and density of the hard ball indenters used are shown in Table 1, with typical values of Young's modulus and Vickers hardness from the literature.

2.3 Method of measuring (estimating) the coefficient of restitution

In this research, a cemented carbide ball of diameter D = 3.175 mm was dropped in air from a free-fall height h_1 at four values of approximately 25, 49, 100, and 196 cm, and the rebound height was measured visually in 1-mm units, and the coefficient of restitution measurement (estimated value) $\hat{e}$ was calculated from the following Equation.

$$\hat{e} = \sqrt{h_2 / h_1} = \hat{V}_2 / \hat{V}_1 \qquad (2)$$

Table 1 Materials and properties of balls used

Material (Symbol)	Density (g/cm^3)	Young's modulus (GPa)	Vickers hardness (JIS R1607)	Fracture toughness (MPa*√m)	Mass of ball used (g)				
					D =10 mm	6.35 mm	3.175 mm	3 mm	1.5875 mm
Silicon Nitride	3.2	370	(14 GPa)	5	—	—	—	0.05	—
Alumina	3.9	290	(16 GPa)	3～4	—	—	—	0.06	—
Steel	7.9	210	≥ 750 HV	—	—	—	0.13	—	—
Cemented carbide	16	620	(16 GPa)	20	7.8	2.0	0.25	—	0.03

Notice : Material properties of ceramics and cemented carbide are from website of Kyocera company

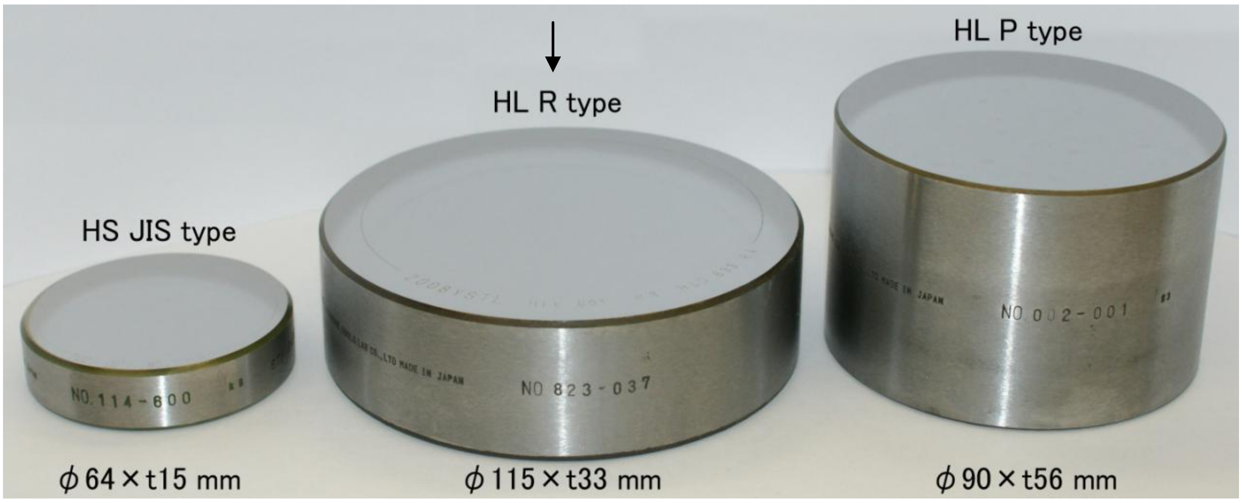

Fig. 2 Appearance of standard blocks for rebound hardness

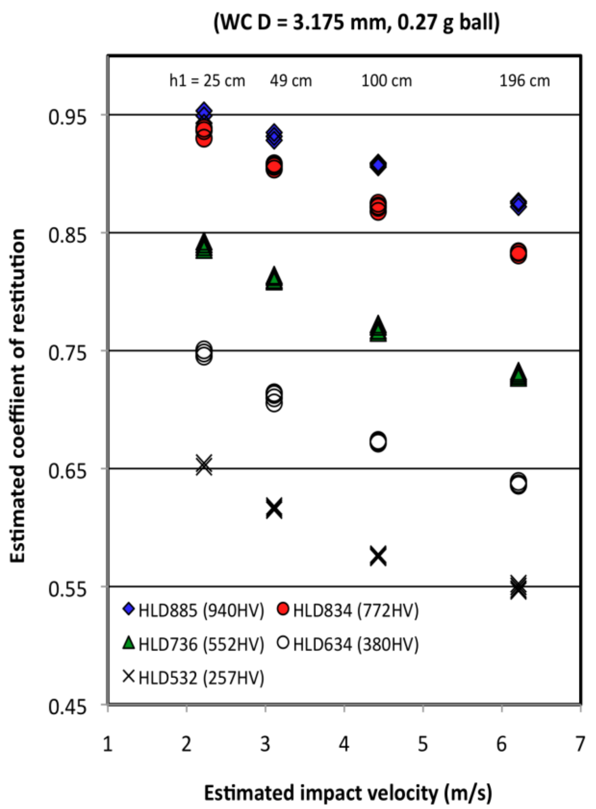

Fig. 3 Influence of impact velocity on estimated coefficient of restitution

In Equation (2), $\hat{V}_1$ and $\hat{V}_2$ are the estimated velocities of the ball indenter in this experiment, immediately before and after impact on the test piece, and the effects of air resistance and so forth are not considered. Throughout this experiment, five measurements were taken for each set of conditions. Fig. 1 shows an example of the measuring tube used in this experiment (dropping device and rebound height measuring tube). Supposing that the error range of each of the three contributing factors, the contact between the measuring tube and the surface of the test piece (zero point setting of the rebound height), the measuring scale (tape measure) and its attachment to the measuring tube, and the visual observation, is approximately 1 mm, then the overall error range of the visual measurement of the rebound height, even in the worst case of a drop height of 25 cm and coefficient of restitution 0.6, is on the order of 3/90 (3.3%) at worst. The effect on the value of the coefficient of restitution can be seen from Equation (2) to be further halved.

2.4 Test piece (hardness standard blocks)

For the test piece in this experiment were used five Leeb hardness standard blocks (Fig.2 HL R type) of HLD hardness 885 (approx. 940 HV), 834 (approx. 772 HV), 736 (approx. 552 HV), 634 (approx. 380 HV), and 532 (approx. 257 HV). These standard blocks were cut from special-purpose eutectoid carbon steel sheet, and subjected to quenching and tempering to achieve the required hardness, with a diameter of 115 mm and thickness of 33 mm, mass of 2.7 kg, which make them larger than the standard blocks (diameter 64 mm, thickness 15 mm, approx. 380 g) generally used for Shore hardness testing and the like(Fig.2 HS JIS type).[6)]

3. EXPERIMENTAL RESULTS

3.1 Effect of drop height (impact velocity) on coefficient of restitution

Since the coefficient of restitution varies with the impact velocity of the hard ball indenter, using a cemented carbide ball of diameter D = 3.175 mm (1/8 inch) and drop height $h_1 \approx$ 25, 49, 100, and 196 cm (respectively $\hat{V}_1 \approx$ 2.2, 3.1, 4.4, and 6.2 m/s), drop tests were carried out on the above five hardness levels of Leeb hardness standard block, the rebound height was visually measured, and an estimated coefficient of restitution $\hat{e}$ was obtained using Equation (2). The results are shown in Fig. 3, and within the range of this experiment, an increased drop height (impact velocity) is associated with a reduced coefficient of restitution, and this effect was found to be somewhat more pronounced in the case of a softer standard block rather than a harder standard

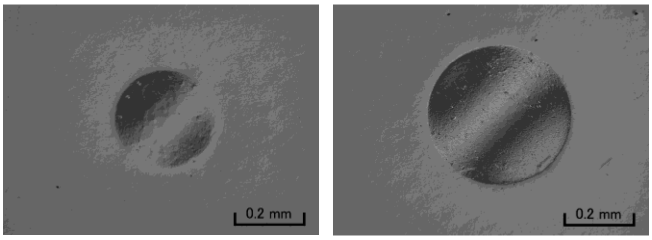

Fig. 4 Indentations of 3.175 mm WC ball on 636 HLD (381HV) standard block observed by Nomarski microscopy
Left h_1 = 49 cm, Right h_1 = 196 cm

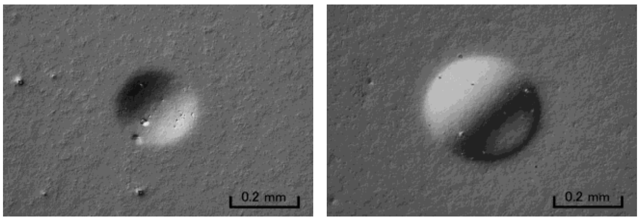

Fig. 5 Indentations of 3.175 mm WC ball on 837 HLD (782HV) standard block observed by Nomarski microscopy
Left h_1 = 49 cm, Right h_1 = 196 cm

block. Figs. 4 and 5 show the indentations formed by free fall from drop heights h_1 = 49 cm and 196 cm, observed by Nomarski microscopy (using different samples of the standard blocks at the same hardness levels as in Fig. 3).

3.2 Effect of hard ball indenter size (diameter) on coefficient of restitution

To investigate the effect of the size (diameter) of the hard ball indenter on the coefficient of restitution, cemented carbide balls of diameter D = 1.5875 mm (1/16 inch), 3.175 mm (1/8 inch), 6.35 mm (1/4 inch), and 10 mm were used, and dropped in free fall from height $h_1 \approx 49$ cm on the above five Leeb hardness standard blocks, the rebound height was visually measured, and an estimated coefficient of restitution $\hat{e}$ was obtained using Equation (2). The results are shown in Fig. 6, and within the range of this experiment, the effect on the coefficient of restitution of the size (diameter) of the hard ball indenter was found to be extremely low, amounting only to a slight reduction in the case of the largest value, D = 10 mm.

3.3 Effect of hard ball indenter material on coefficient of restitution

To obtain correct hardness testing results, it is generally advised to have an indenter at least 1.5 times harder than the test piece.[4)] Moreover, considering the influence of the "mass effect" on rebound hardness testing, in addition to the hardness of the hard ball indenter, its mass (density) can be expected to be an important factor. Therefore, in addition to the cemented carbide ball of diameter D = 3.175 mm, alumina ceramic and silicon nitride ceramic balls of diameter D = 3 mm were used, and dropped in free fall from height $h_1 \approx 49$ cm onto the five Leeb hardness standard blocks described in section 2.4, the rebound height was visually measured, and an estimated coefficient of restitution $\hat{e}$ was obtained using Equation (2). Although not sufficiently hard for use as an indenter, the experiment was also carried out with a steel bearing ball under the same conditions. The results are shown in Fig. 6, and although not a comparison with exactly the same diameter, within the range of this experiment, the coefficient of restitution was greatest for the steel bearing ball, followed by silicon nitride ceramic, alumina ceramic, and cemented carbide balls in that order. The difference in the coefficient of restitution between the hardest standard block and softest standard block was greatest for cemented carbide at 0.31, and was otherwise around 0.2. For reference, testing was also carried out with a ruby (transparent red) and sapphire (transparent colorless) balls of diameter D = 3 mm, and the results were similar to those for the alumina ceramic ball shown in Fig. 7.

When a steel bearing ball impacts a test piece of high hardness, plastic deformation is likely to occur, so it is clear that this is not suitable for the indenter of this testing method. It was used purely for the purposes of comparison with other materials.

4. CONSIDERATIONS

4.1 Hard ball indenter impact velocity

As can be seen in Fig. 3, the drop height must provide a sufficient impact velocity, particularly in the region of high hardness values, to obtain clear differences in the coefficient of restitution for test pieces of different hardness values. The reduction in the coefficient of restitution with increasing impact velocity was somewhat greater for softer test pieces, and in order to precisely distinguish the hardness of test pieces, it is considered that the impact velocity should be set to at least a certain value.

For practical implementation of this testing method, it will be necessary to consider the stability of the hard ball indenter impact velocity, but the results of this experiment suggest that a 1% fluctuation in the hard ball indenter impact velocity would give rise to a fluctuation of between 0.1% and 0.2% in the coefficient of restitution. Again, when predicting the indenter velocity by measuring the height from which it is dropped, it is of course the case that the higher the indenter velocity the greater the air resistance, and in this experiment, particularly when the drop height h_1 is high or the test piece hardness is high, the experimental error in the measurement (estimated value) of the coefficient of restitution $\hat{e}$ is thought to be large.

4.2 Hard ball indenter size

In the Vickers hardness test and others which use a pyramidal indenter, ideally for uniform test pieces a law of similarity holds with the hardness, and regardless of the testing load or dimensions of the indentation, since the strain is constant the same hardness value can be expected. In comparison, when testing with a ball indenter as in Brinell hardness, the law of similarity for the hardness holds only when the strain is constant, as follows.

$$d / D = Const. \qquad (3)$$

Where D is the ball indenter diameter, and d is the indentation diameter.

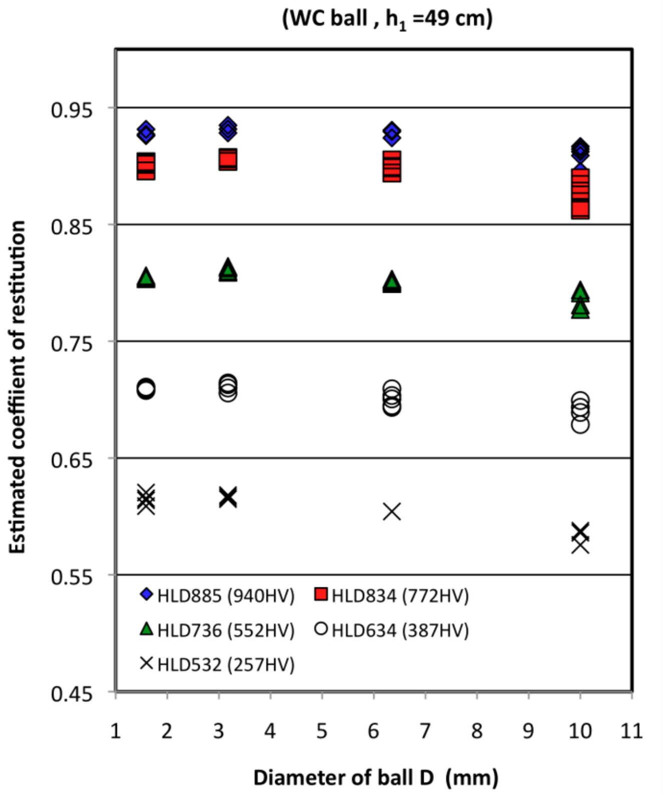

Fig. 6 Influence of ball diameter on estimated coefficient of restitution

When the hardness value H is seen as the mean pressure into the material, H can be found from the ratio of the pressure load to the area of the indentation, but this can be replaced by the ratio of the kinetic energy imparted to the test piece by the indenter to the volume of the resulting indentation, so that if m is the mass of the hard ball indenter, this can be represented as:

$$H \propto m V_1^2 / d^3 \qquad (4)$$

Since the hard ball indenter mass m is proportional to the cube of the diameter D, Equation (4) can be rewritten as:

$$H \propto V_1^2 (D/d)^3 \qquad (5)$$

Therefore, for a test piece of hardness value H, impacted by a hard ball indenter at constant velocity V_1, the following holds:

$$d/D = Const. \quad (\text{when } H \text{ and } V_1 \text{ are constant}) \qquad (6)$$

Since a law of similarity for the hardness as shown in Equation (3) is satisfied, the same strain is applied regardless of the size of the hard ball indenter, and as a result the same hardness measurement value can be expected.

The results of this experiment shown in Fig. 6 support this observation clearly, and suggest that in rebound hardness testing, a law of similarity for hardness holds in the same way as for Vickers hardness, and that regardless of the size of the hard ball indenter a consistent hardness scale can be established.

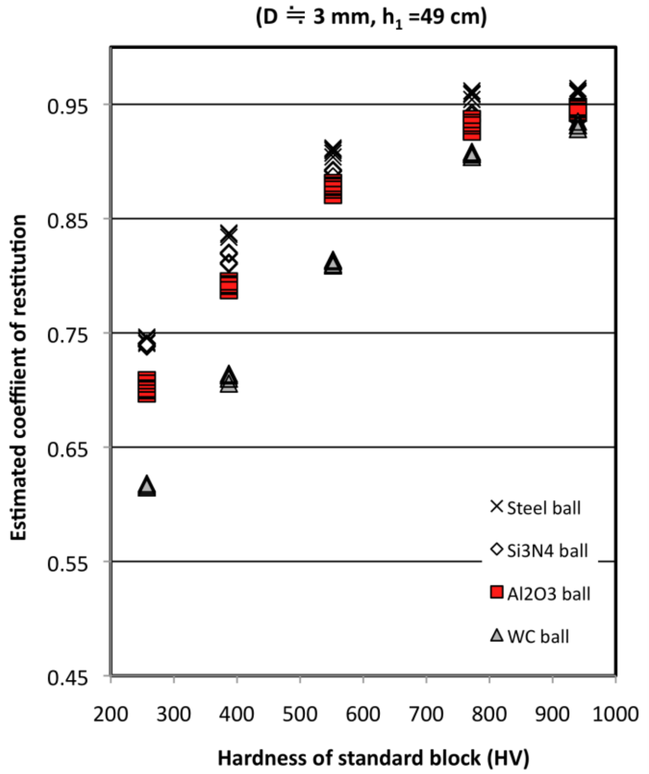

Fig. 7 Influence of ball materials on estimated coefficient of restitution

Further, in a test such as the Vickers hardness test, regardless of the testing load, the strain applied to the test piece is viewed as constant, and if the rate of increase of the testing load over time is constant, that is, if the testing load increases substantially linearly over time, then if the time Δt required to form the indentation is the same, the testing can be considered to be carried out at the same strain rate, regardless of the load or the dimensions of the indentation. In contrast, for rebound hardness testing with a hard ball indenter, this can primarily be expressed as:

$$m(V_1 + V_2) = m V_1 (1 + e) = F \cdot \Delta t \qquad (7)$$

Now by representing the mass m of the hard ball indenter by its diameter D, and replacing the testing load F by the hardness H of the test piece and the size d of the indentation, we can represent this as follows:

$$\Delta t \propto D \cdot (D/d)^2 \cdot \frac{V_1}{H} \qquad (8)$$

As shown by expression (5), when testing a test piece of hardness H with impact velocity V_1, D/d is constant, and therefore in Equation (8) the time taken to form the indentation is considered to be proportional to the size of the hard ball indenter. Therefore, in rebound hardness testing with a hard ball indenter, since the strain rate can be considered inversely proportional to the size of the hard ball indenter, for a material of high sensitivity to the strain rate, depending on the size of hard ball indenter used, it is expected to be a slight variation in the coefficient of restitution or hardness measurement.

4.3 Hard ball indenter material

In considering the practical implementation of hardness testing by the HNM method, the selection of the hard ball indenter material is important: (1) the ball indenter should be readily available, and in quality of reliability and high durability, and in addition, (2) it is preferable to select a material with a large difference in the coefficient of restitution *e* between a hard test piece and a soft test piece. At the same time, (3) to achieve a testing method in which the "mass effect" is as small as possible, the density and other properties of the hard ball indenter must also be considered. In particular the results of this experiment show results for a cemented carbide ball which are significantly different from the others, and by considering the Young's modulus, hardness, density and other properties it is essential to understand the reason for this.

4.4 Influence of "mass effect" on test piece

In this experiment, a large steel standard block of mass approximately 2.7 kg was used as the test piece, but in cases where the mass or impact velocity was high the mass of the test piece was clearly insufficient, and an unnatural reduction in the coefficient of restitution or increased fluctuation in the measurement values was found. Therefore, based on the considerations in section 4.3, if this testing is implemented with a very small hard ball indenter, the "mass effect" is not a big concern, and moreover it is thought that testing results consistent with those from testing with a large hard ball indenter can be obtained, and thus practical implementation of a very small rebound hardness test is considered possible.

4.5 Definition of a rebound hardness scale by the HNM method

To summarize sections 4.1 through 4.5, in considering practical implementation of a hard ball indenter rebound hardness test by the HNM method, it will be seen that by selecting a hard ball indenter material and impact velocity most appropriate for industrial hardness testing by this testing method, as for Vickers or micro-Vickers hardness, a uniform hardness scale not dependent on the magnitude of indentation dimensions can also be defined for rebound hardness testing.

In the notation for Vickers hardness, the testing load is appended to the hardness symbol HV, but in principle whatever the load this can be seen as the same HV hardness. Therefore, for a hardness scale using this testing method, it is proposed that for the hardness symbol, for example HNM could be used, and the value of the diameter D of the hard ball indenter appended, enabling the expression of a uniform hardness scale not dependent on the hard ball indenter or indentation size.

5. CONCLUSIONS

The conclusions of this research can be summarized as follows.

(1) By the HNM method, if hardness testing is carried out based on the coefficient of restitution of a hard ball indenter, then an unprecedented rebound hardness scale can be obtained, with a uniform law of similarity for hardness. Moreover, by using a very small hard ball indenter, the "mass effect" can be greatly reduced.[7)]

(2) Although as described above a law of similarity holds for the hardness, for materials with a large velocity effect, the impact time will vary depending on the size of the hard ball indenter used, and therefore the test results can be expected to be affected.

(3) In order to precisely distinguish the hardness of test pieces, the selection of impact velocity and hard ball indenter material is considered to be particularly important.

(4) In this demonstrating experiment, free fall of a hard ball indenter was used, but if the drop height or rebound height is particularly high, or if the ball diameter is large, or the density low, then the effects of air resistance and so forth on the estimated value of the hard ball indenter velocity may be unavoidable.

(5) Implementing the HNM method with a free-fall dropping device has the advantages that the rebound height can be measured visually with relatively high accuracy, and also of being inexpensive, but it can only be used for testing in the perpendicular direction, and the measuring tube is bulky and not very portable.

In order to establish the HNM method as an industrial hardness testing method, and to evaluate the above described effects and problems more accurately, more work is required to develop a forced ejection device for a hard ball indenter and a speed detection mechanism.

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