

## STUDY ON SIMILARITY LAW OF HARDNESS USING SMALL BALL REBOUND TEST, eNM

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**Abstract:** We investigated the law of similarity for hardness with respect to a newly-developed small ball rebound hardness test method. In the case of a spherical indenter hardness test such as that used for Brinell hardness, only if  $d/D$  were a constant, where  $d$  is the diameter of the indentation and  $D$  is the diameter of the spherical indenter, would the indentations and the deformation regions caused by spherical indenters of different sizes have similar shapes, and therefore allow the same hardness values to be obtained. Using hardness blocks of 200 to 900 HV made of eutectoid carbon steel as specimens, as the measure of hardness we investigated the coefficients of restitution for 5, 3, and 2 mm alumina ceramic ball indenters with an impact velocity of 10 m/s. The test results were that the coefficients of restitution agreed well with the values of  $d/D$  for spherical indenters of different sizes, so we believe that this test method is a rebound hardness test method that satisfies the law of similarity for hardness, as is true for Vickers hardness.

**Keywords:** Law of similarity for hardness, rebound hardness, hardness reference block, coefficient of restitution

### 1. PURPOSE

In conventional rebound hardness test methods there is the problem of the mass effect, that is, the impossibility of accurately measuring the hardness of a small specimen with a mass of a several kilograms or less. The authors have performed research into the practical application of a small ball rebound hardness test method according to an invention of Nakamura, Maki, et al., as a test method that can make a breakthrough reduction in the mass of the specimen<sup>1)-4)</sup>. In this method the indenter is not embedded in a hammer or in a metal part called an “impact body”, as it is in conventional methods, but rather it is possible to use a hard, lightweight, spherical single body as-is for the indenter that is injected, thereby realizing a breakthrough reduction in the mass effect. This is not the only advantage of making the ball an indenter that is a single body, because we also theoretically expect the law of similarity for hardness<sup>1)2)</sup> to hold, and so we performed the following experiment to verify this.

### 2. THE LAW OF SIMILARITY FOR HARDNESS

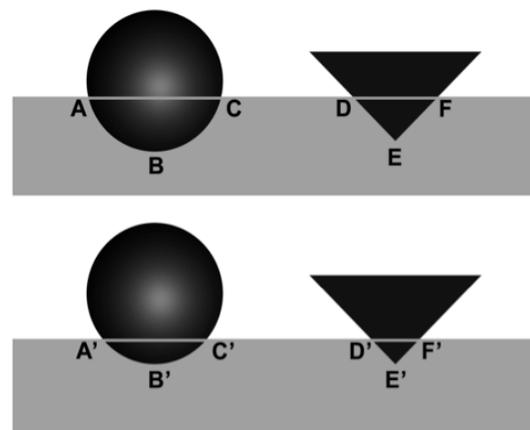
If one injects a given indenter into an ideally homogeneous specimen with various test forces, in the case

that the indenter has a pyramidal shape as it is for Vickers hardness, the shape of the indentation and the region of deformation around the indentation should be similar regardless of the magnitude of the test force, so that one can expect to obtain the same hardness value. This is the law of similarity for hardness, and the case of a conical indenter is similar, although this generally is not used. On the other hand, in the case of a spherical indenter, which is used such as for Brinell hardness, or the case of small ball rebound hardness, if the test force is varied for the same indenter then the shape of the indentation and the deformation region will not be similar, so the obtained hardness value will change. This relationship is shown schematically in Figure 1.

In order for the law of similarity for hardness to hold for a spherical indenter it is necessary to use a technique that changes the diameter  $D$  of the spherical indenter according to the magnitude of the test force  $P$ . Specifically, the test must be performed under the condition of satisfying the following equation:

$$\frac{P}{D^2} = Const \quad (1)$$

If this equation is rewritten in terms of the relationship between the indentation size  $d$  and the diameter  $D$  of the



**Figure 1.** The indentation shapes of pyramidal or conical indenters are similar (right), but not in the case of a spherical indenter (left).

spherical indenter, it becomes:

$$\frac{d}{D} = Const \quad (2)$$

Since the ratio of the diameters of the spherical indenter and the indentation is constant, one can see that the deformations will be geometrically similar shapes.

In the case of an indentation due to the impact of a spherical indenter, as has been clarified in a previous report<sup>2)</sup>, we believe that the relationship of formula (2) will hold if hardness is expressed as a relationship between the impact energy and the indentation volume.

### 3. EXPERIMENTAL METHOD

For the experiment we used the four small ball rebound hardness trial test machines of different indenter diameters shown in Table 1 and Figure 2. For the specimens we used 20 pieces each of the 5 types of reference pieces made of eutectoid carbon steel shown in Figure 3 and Table 2, with nominal hardnesses of 95, 80, and 60 HS, 30 HRC, and 30 HS (corresponding to 900, 700, 450, 300, and 200 HV).  $\phi$  5, 3, and 2 mm alumina spherical indenters were injected into the reference pieces at 10 m/s, and we measured the coefficient of restitution  $e$  at each of 10 points. According to the small ball rebound test method, the coefficient of restitution is defined to be:

$$e = \frac{V_2}{V_1} \quad (3)$$

where  $V_1$  is the injection speed of the spherical indenter ( $V_1 = 10$  m/s) and  $V_2$  is the rebound velocity from the specimen.

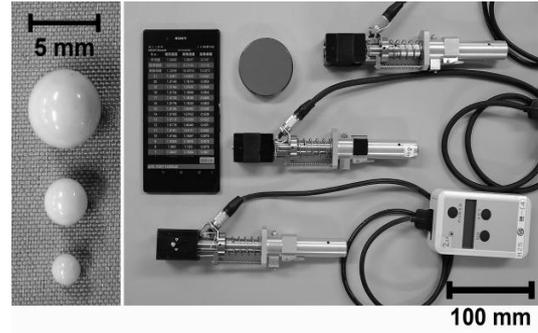
In conventional rebound hardness tests such as Shore, which has a large mass effect, it is not possible to measure reference pieces as-is with the usual sizes used in this experiment, so it is necessary to test using a JIS type of machine casing with a mass of 8 kg, but the small ball rebound hardness test of the present experiment has a small mass effect, as previously reported<sup>3)</sup>, and we preformed the test by placing all the reference pieces with a mass of 380 g as-is on a wooden table.

**Table 1. eNM Testing Machines Used**

Testing Machine Used	Diameter and Mass of Spherical Indenter (Alumina)
eNM 5A (2014)	$\phi$ 5 mm, 0.258 g
eNM 3A (2014 Type I) eNM 3A (2014 Type II)	$\phi$ 3 mm, 0.056 g
eNM 2A (2014)	$\phi$ 2 mm, 0.016 g

In order to compare the coefficient of restitution and the Vickers hardness, for the Shore hardness reference pieces whose Vickers hardness values had already been obtained by the VHS method of the JIS we used those HV values<sup>5)</sup>, and for the 30 HRC reference piece we performed a separate Vickers hardness test and used that HV value.

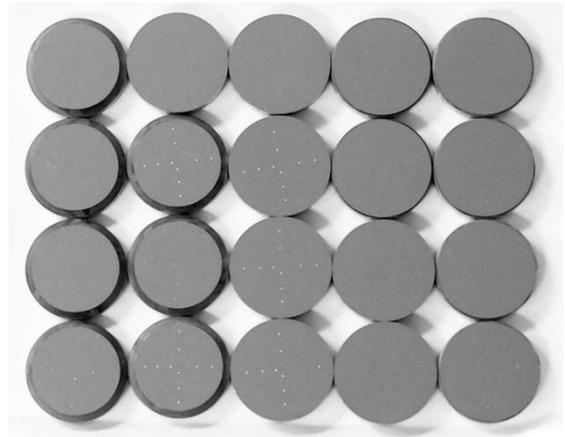
(Note: We changed the name of the experimental machine of this experimental method from the conventional



**Figure 2.** Aluminum ball indenters (left). Testing machines (for  $\phi$  5, 3, and 2 mm balls) and a hardness block ( $\phi$  64  $\times$  t15 mm, 380 g)

**Table 2.** Average Vickers Hardness and Other Specifications of the Hardness Blocks (20 blocks for each hardness level.)

Nominal Hardness	Material, Dimensions, and Mass	Vickers Hardness (HV)
95 HS	SK85, $\phi$ 64 $\times$ t15, 380 g	911
80 HS		693
60 HS		457
30 HRC		292
30 HS		195



**Figure 3.** Appearance of the hardness blocks used as specimens. (20 blocks were manufactured as one batch for a given hardness level.)

“HNM” to “eNM”, since it is associated with the coefficient of restitution  $e$ <sup>3)4)</sup>.)

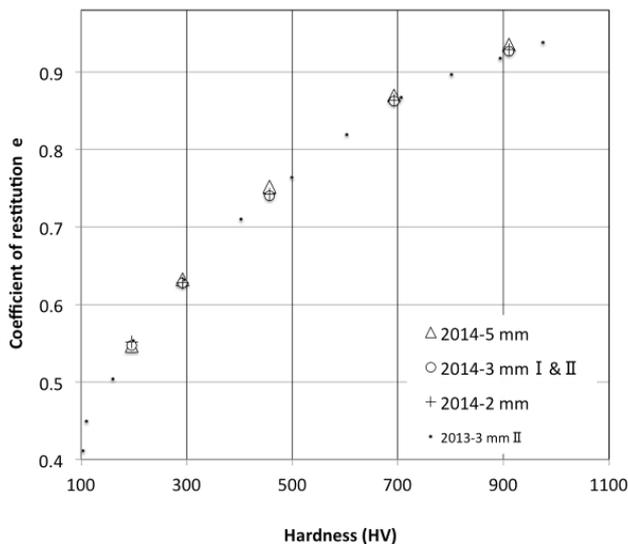
### 4. EXPERIMENTAL RESULTS

For the diameters that ranged from 2 to 5 mm of the alumina spherical indenters, as shown in Table 3 and Figure 4, regardless of the size of the spherical indenter, for the same hardness level approximately the same coefficient of

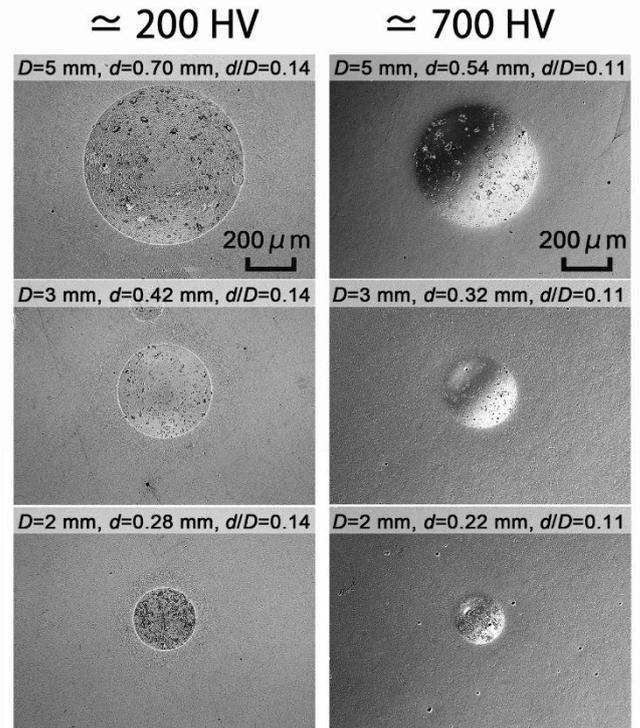
restitution was measured, so we verified that the law of similarity for hardness holds, i.e., that it does not depend on the diameter of the indenter. As a reference, the figure uses a small plot<sup>4)</sup> to show the results of measuring the coefficient of restitution using a 3-mm alumina spherical indenter and Vickers hardness reference pieces (including ones not made from eutectoid carbon steel) that were previously reported, and the results of the present experiment are approximately the same as the previous results. From observing the indentation generated in the reference pieces made of eutectic carbon steel with Vickers hardnesses of approximately 200 HV and 700 HV, as shown in Figure 5, regardless of the size of the spherical indenter,  $d/D$  was approximately 0.14 for the 200 HV level, and approximately 0.11 for the 700 HV level, which are approximately the same. Also, from directly observing the indentations, it can be verified that the law of similarity for hardness holds, i.e., that it does not depend on the diameter of the indenter.

**Table 3.** Average coefficients of restitution  $e$  obtained using alumina ball indenters (at  $V_1 = 10$  m/s) and hardness reference blocks for Vickers hardness. (20 blocks for each hardness level.)

Nominal Hardness of the Block	Vickers Hardness (HV)	Coefficient of Restitution $e$ (alumina ball, $V_1 = 10$ m/s)		
		5 mm Ball	3 mm Ball	2 mm Ball
95 HS	911	0.936	0.927	0.929
80 HS	693	0.870	0.863	0.864
60 HS	457	0.752	0.741	0.742
30 HRC	292	0.633	0.628	0.628
30 HS	195	0.546	0.547	0.552



**Figure 4.** Relationship between coefficients of restitution  $e$  obtained by using alumina ball indenters (at  $V_1 = 10$  m/s) and hardness standard blocks, and the Vickers hardness.



**Figure 5.** Indentations caused by 5, 3, and 2 mm alumina ceramic balls at  $V_1 = 10$  m/s. Left: 200 HV hardness block (bright-field image). Right: 700 HV hardness block (Nomarski image)

Also, within the range of this experiment, even for the alumina spherical indenter with a diameter of 5 mm, which had the largest mass and the largest impact energy on the specimen, the coefficient of restitution did not decrease and the occurrence of a mass effect was not seen. Therefore, for reference pieces within the hardness range of this experiment we believe that even a 5-mm spherical indenter can be used without the need to worry about a mass effect.

As a separate issue from the law of similarity for hardness, the time required to form the indentation due to the impact of the spherical indenter does depend on the diameter of the spherical indenter, so that if a material has strong strain rate sensitivity then that may lead to a difference in the coefficient of restitution or  $d/D^2$ , but this could not be verified in this experiment. Also, we believe that the small differences (approximately 1%) in the coefficients of restitution among the test machines in this experiment were due to

manufacturing differences among the individual test machines, rather than being an intrinsic problem with this experimental method.

## 5. SUMMARY

The following were the results of measuring the coefficient of restitution  $e$  of hardness reference pieces (JIS Shore type) made of eutectoid carbon steel with a hardness of approximately 200 to 900 HV,  $\phi 64 \times t15$  mm,

and mass 380 g, using alumina hardness spherical indenters with a diameter from 2 to 5 mm and an injection speed of 10 m/s.

- (1) Even for different spherical indenter diameters approximately the same coefficient of restitution was obtained, so we verified that the test method satisfies the law of similarity for hardness in the sense that even for indenters with different diameters, for small ball rebound hardness the same hardness value (coefficient of restitution) can be obtained.
- (2) Therefore, with this test method, it is expected that the diameter of the hard spherical indenter will be chosen according to factors such as the size, surface roughness, and mass of the material that constitutes the specimen, making it possible to evaluate hardness and the coefficient of restitution on the same scale.
- (3) For reference pieces in the hardness range of this experiment, even for a 5-mm alumina spherical indenter, we believe that there is no problem due to the mass effect when measuring the coefficient of restitution of the JIS-type Shore hardness reference pieces.

This experiment is part of the research results of a Chiba Prefecture manufacturing subsidy, and we wish to thank Drs. Nakamura and Maki who provided guidance, and all those who cooperated with us.

## 6. REFERENCES

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