

# DISCUSSION ON THE MASS EFFECT OF REBOUND HARDNESS THROUGH THE DEVELOPMENT OF THE SMALL BALL REBOUND HARDNESS TESTING MACHINE

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**Abstract:** Rebound hardness is a popular onsite testing method to evaluate the hardness of heavy and massive metal parts and products. However, such rebound testers are sometimes wrongly applied to small specimens that do not have enough mass. In such a case, impact energy is partly “leaked” through the vibration of the specimen and this leads to a lowered and wrong value of the coefficient of restitution. This phenomenon is called a “mass effect,” and it is mainly caused by a heavy impact body mounted with a diamond or cemented carbide tip indenter.

In 1987, Nakamura and Maki et al. developed a new rebound hardness tester to avoid the mass effect by using a small steel ball without an additional impact body. However, the testing direction is limited to upward only because launching a small ball in any direction was not easy at that time.

In this paper, a prototype of a small ball rebound hardness tester (HNM-2012) in any direction was developed and the mass effect investigated and compared with conventional testers, using JIS Shore hardness standard blocks ( $\phi 64 \times t 15 \text{mm}$ , 380g). The advantage of a small ball rebound hardness tester is confirmed because no mass effect was observed for the tester, whereas conventional rebound testers showed a significant mass effect.

**Keywords:** Rebound hardness, Shore hardness, Leeb hardness, Mass effect, Hardness standard blocks

## 1. INTRODUCTION

Rebound hardness testing evaluates the hardness of a test specimen by having an indenter, which is called a hammer or an impact body, strike a test specimen at a controlled velocity and measuring the height and velocity of its rebound. This is a widely used on-site testing method for evaluating the strength of large pieces of equipment and structures that are difficult to test with a stationary hardness tester [1, 2]. However, conventional rebound hardness testers, for which it is difficult to make the mass of an impact body sufficiently small, involve a problem related to the mass effect of a test specimen. That is, if they are used to test a thin, lightweight specimen, the kinetic energy of the impact body is lost not only due to plastic and elastic

deformation, but also to the specimen vibrating, resulting in inaccurate hardness values.

However, the small ball rebound hardness test method developed by Nakamura and Maki, et al. [3] chiefly for studying the mechanism of the plastic deformation of metals, which uses a small ball that impacts a test specimen, can reduce the mass effect significantly. Therefore, there had been expectations for the industrial application of this method. However, this was not achieved because it was difficult at that time to eject a ball in any desired direction and there were limitations on the material of the ball indenter, which were attributable to the theory of the indenter speed detection mechanism.

Based on a renewed recognition of the theoretical advantages of the small ball rebound hardness test [4], the authors developed the prototype HNM-2012 small ball rebound hardness tester by incorporating solutions for the problems that have hindered practical application of the test. The mass effect of the prototype machine was then evaluated as described below.

## 2. EXPERIMENTAL METHOD

### 2.1 Testers examined

To evaluate the mass effect of the prototype HNM-2012 small ball rebound hardness tester, one each of Shore (HSD) and Leeb (HLD) hardness testers were used as conventional rebound hardness testers to be compared with the prototype HNM-2012. Fig. 1 and Fig. 2 show the appearances of the HNM-2012, HSD, and HLD testers.

#### 2.1.1 Prototype HNM-2012 small ball rebound hardness tester (HNM -2012)

The small ball rebound hardness test is carried out by having a small hard ball impact a test specimen and calculating the proportion of the ball indenter velocity immediately after impact ( $V_2$ ) to the ball indenter velocity immediately before the impact ( $V_1$ ), which is defined as the coefficient of restitution  $e$  to be used as an indicator of hardness.

$$e = \frac{V_2}{V_1} \quad (1)$$

The prototype HNM-2012 tester consists of a ball holder that retains the small ball before it is ejected in any desired direction, a launcher for the forced ejection of the ball, a detector that photoelectrically measures time  $T_1$  and  $T_2$  when

the ball passes a reference point before and after hitting the test specimen, and a processor that processes data from the detector and indicates time  $T_1$  and  $T_2$  measured and coefficient of restitution  $e$  calculated.

The exit end of the ejection device of the HNM 2012 tester contacts the surface of the test specimen. The distance from which to the sensor in the detector was set at 10 mm or 20 mm. To minimize the mass effect, an alumina ball indenter with a diameter of 3 mm and a mass of around 55 mg was used. The impact velocity  $V_1$  was set at 10 m/s

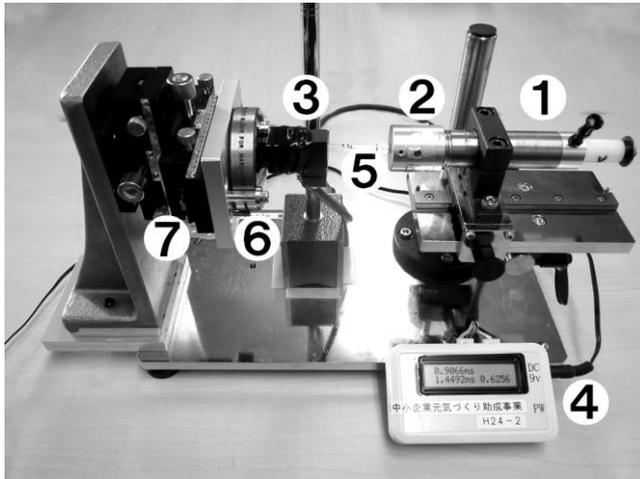


Fig. 1 Appearance of the small ball rebound hardness tester (HNM-2012) when launching the ball horizontally.

- ① Launcher, ② Ball holder, ③ Sensor, ④ Processor (Indicator) ⑤ Connecting tube (between ball holder and sensor), ⑥ Specimen, ⑦ X-Y stage



Fig. 2 Appearances of the conventional rebound hardness testers and standard blocks.

- ① Shore hardness tester (HSD), ② JIS type anvil for HS tester, ③ Leeb hardness tester (HLD) and its indicator  
④ HS standard block (JIS type: φ64 × t 15 mm)  
⑤ HLD standard block (MTRAJ Roll Committee type: φ115 × t 33 mm)

( $0.9700 \leq T_1 \leq 1.0399$  ms). Because the impact of the gravitational acceleration on the ball velocity is negligible, as far as this experiment is concerned, no adjustments were made [3]. Table 1 shows the specifications, such as indenter geometry and impact velocity, of the HNM-2012 tester and the conventional rebound hardness testers detailed below.

### 2.1.2 Shore hardness tester (HSD)

The HSD tester uses an impact body, called a hammer, which has a diamond embedded that has a tip radius of about 1 mm and a mass of around 36 g. The hammer free falls from a height of about 19 mm ( $= h_1$ ) onto a test specimen, and rebound hardness  $h_2$  is measured with a dial gauge. This tester has the advantage of not requiring a power supply and other accessories.

$$HSD = 140 \frac{h_2}{h_1} \quad (2)$$

However, the test can only be conducted in the vertical direction, because it relies on a free-falling hammer. The minimum mass of a test specimen that is not subject to the mass effect is considered to be about 4 kg. If a JIS-type HS standard block of about 380 g in mass (see Fig. 2④) has to be used to verify the HSD tester, or the rebound hardness of a thin, lightweight specimen needs to be measured, a JIS-compliant tester frame (see Fig. 3) consisting of a 4-kg-in-mass steel anvil integral with a 4-kg-in-mass arm on which the tester is suspended needs to be used [5].

### 2.1.3 Leeb hardness tester (HLD)

Due to the success of the Vickers/Shore hardness conversion method, or the VHS method proposed by Professor Yoshizawa and standardized by the JIS committee, the Shore hardness test method has been extensively applied industrially in Japan for testing rebound hardness. However, in many of the other countries, which do not have the VHS or equivalent conversion method, use the Leeb harness (HLD) test method instead of the Shore method. The Leeb hardness method determines hardness by magnetically measuring the impact body's velocities  $V_1$  and  $V_2$  and multiplying the coefficient of restitution  $e$  by a constant [6].

$$HL = 1000 \frac{V_2}{V_1} \quad (3)$$

The HLD tester uses an impact body of nearly 6 g in mass embedded at its tip with a cemented carbide indenter of 1.5 mm in tip radius, which is forcibly launched in any desired direction and does not free fall on a test specimen. Therefore, this method is not restricted to testing in the vertical direction.

Because no special tester frame is supplied for the HLD tester, as it is for the HSD tester, a large standard block of 2.7 kg in mass is used for verifying the HLD tester (Fig. 2 ⑤). If a thin, lightweight material has to be tested, coupling paste must be applied on the bottom face of the tested material so that it adheres securely to an anvil of sufficient mass.

## 2.2 Anvils

### 2.2.1 Steel anvil

In the conventional rebound hardness tests, mass effect can be ignored if an anvil of several kilograms or heavier is

Table 1 Specifications of indenter of rebound hardness testers

Scale	Material	$r$ mm	$m$ g	$h_1$ mm	$V_1$ m/s	$E$ mJ
HSC HSD	Diamond	1	2.5 * 36.2 *	254 19	(2.2) (0.6)	6.2 6.7
HLD HLE	Cemented carbide Diamond	1.5	5.45 *	—	2.1	12.0
HNM-2012	Alumina	1.5	0.055	—	10	2.8

$r$  : tip radius,  $m$  : mass (\* : includes impact body),  
 $h_1$  : free-fall height,  $V_1$  : impact velocity,  
 $E$  : kinetic energy of impact

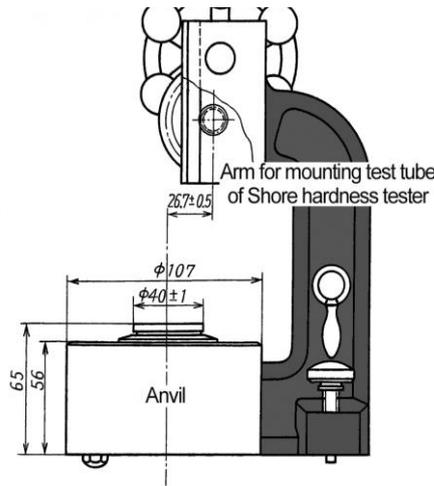


Fig. 3 Dimensions (mm) of anvil for JIS HS testers.

used, even when a thin, lightweight material is tested. Therefore, we decided to use the aforementioned HSD tester frame for the experiments discussed here. However, because the arm of the tester frame interfered with the operation of the hardness meter of the HLD tester, the relevant part of the arm was cut off and the remaining arm weighing about 1.7 kg integrated with a 4-kg-in-mass anvil was used for the experiments.

### 2.2.2 Wood anvil

As opposed to the steel anvil mentioned above, a light and structurally weak wood anvil is required to clearly detect the mass effect of the testers under review. Therefore, a cedar wood anvil of 100 mm in diameter, 56 mm in thickness, and 120 g in mass was used.

### 2.3 Test specimen

The JIS standard for Shore hardness test—Calibration of reference blocks [7] prescribes the use of a hardness reference block of 64 mm in diameter and 15 mm in thickness. The Vickers hardness value of such a reference block can be converted into a Shore hardness (VHS) value using the equation below, according to the aforementioned VHS method. Unlike conversions of physical quantities, conversions of hardness values can suffer a significant decline in credibility, unless the type of steel used for the reference block is restricted. Therefore, it is restricted to eutectoid carbon steel SK85 (or SK120 in the higher hardness ranges).

$$\text{VHS} = \left\{ 1.7435 \left( \frac{\text{HV}}{1000} \right) - 1.1505 \left( \frac{\text{HV}}{1000} \right)^2 \right.$$

(4)  $0.5818 \frac{\text{HV}}{e^{100}}$

For the experiments discussed here, we used three each of 90, 60, and 30 HS (Shore hardness) reference blocks that comply with the aforementioned JIS standard, because they are most commonly used for rebound hardness testing. These HS values roughly correspond to 800, 450, and 200 HV (Vickers hardness), respectively. The blocks were tested using the three types of rebound hardness tester with two different anvils by making and measuring five indentations in the diametrical direction on the block's testing surface, as shown in Fig. 4. Table 2 shows the HS (VHS) values of the tested Shore hardness blocks, along with the average and uniformity of the Vickers hardness values from which the HS (VHS) values were obtained.

Table 2 HS Standard blocks used as specimens

Nominal hardness (HS)	Block No.	Material	Vickers hardness (n=5×2)		VHS
			Avg.	CV %	
90	122-737	SK85	805.3	0.5	89.4
	122-738		803.8	0.3	89.3
	122-739		805.8	0.4	89.4
60	122-516		459.1	0.4	60.7
	122-517		457.3	0.7	60.5
	122-519		457.9	0.5	60.6
30	122-277		196.6	0.4	30.3
	122-278		195.6	0.3	30.1
	122-279		196.8	0.2	30.3

## 3. EXPERIMENTAL RESULTS

We tested the 90, 60, and 30 HS Shore hardness blocks on steel and wood anvils using the HNM-2012 tester and conventional HSD and HLD testers. The hardness values obtained, which are expressed as a coefficient of restitution  $e$  for the HNM-2012 tester, were compared for the steel and wood anvils.

### 3.1 Difference in coefficient of restitution between the two anvils when tested with the HNM-2012 tester

Fig. 5 shows how the hardness test was conducted using the HNM-2012 tester with the test specimen on steel and wood anvils.

Fig. 6 shows the test results, which were in good agreement between the structurally weak wood anvil and the steel anvil for all hardness levels tested. In addition, there was no significant difference in the test results for a test position close to the edge of the block or at its center.

### 3.2 Difference in rebound hardness between the two anvils when tested with the HSD tester

As shown in Fig. 7, hardness measurements obtained with the HSD tester were clearly lower for the wood anvil than for the steel anvil. The differences were about 25 HS and 45 HS when tested at the center and edge, respectively, of the

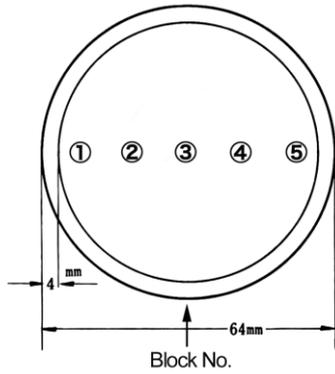


Fig. 4 Five testing positions on the specimens (JIS HS standard blocks)



Fig. 5: Testing operation of HNM-2012 when launching the ball vertically (downward)  
 Left: Test specimen on steel anvil  
 Right: Test specimen on wood (Cedar) anvil

90 HS block. This clearly shows the so-called edge effect, or a phenomenon whereby lower hardness measurements are obtained closer to the periphery of the block [8]. The same phenomenon was also observed with the other two blocks: with the 60 HS block, the difference in hardness measurements was about 20 HS at the center, compared to 30-35 HS at the edge; with the 30 HS block, the difference was around 10 HS at the center, compared to nearly 20 HS at the edge. The tendency of lower hardness measurements closer to the edge of the block is more marked with a harder test specimen.

It should be noted that, unlike HNM and HLD values, HS hardness represents a change in the kinetic energy of an impact body, not a ratio of velocities of the small ball or the impact body, immediately before and after impact.

### 3.3 Difference in rebound hardness between the two anvils when tested with the HLD tester

The test results for the HLD tester are shown in Fig. 8, which show the aforementioned edge effect, as well as a tendency of lower hardness measurements on the wood anvil than on the steel anvil. The magnitude of the difference between the two anvils, however, was not significant among the three hardness levels of blocks tested. For all hardness levels, hardness measurements obtained on the wood anvil were lower than those on the

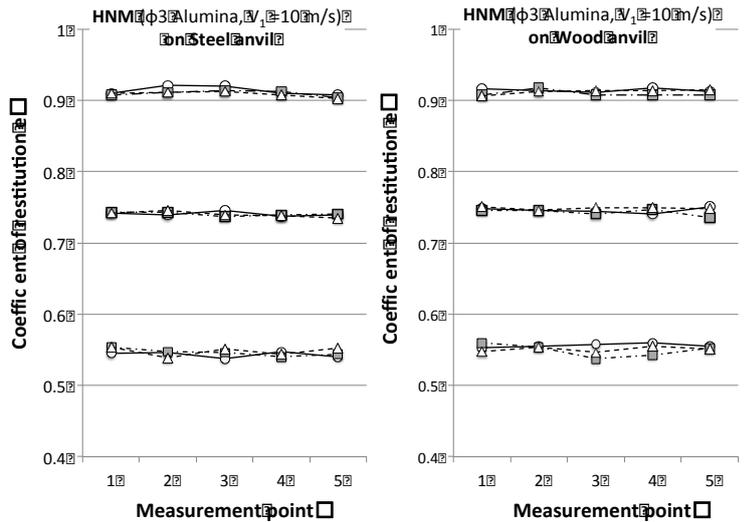


Fig. 6 Coefficient of restitution of JIS HS standard blocks obtained with the HNM-2012 tester on steel anvil and wood anvil.

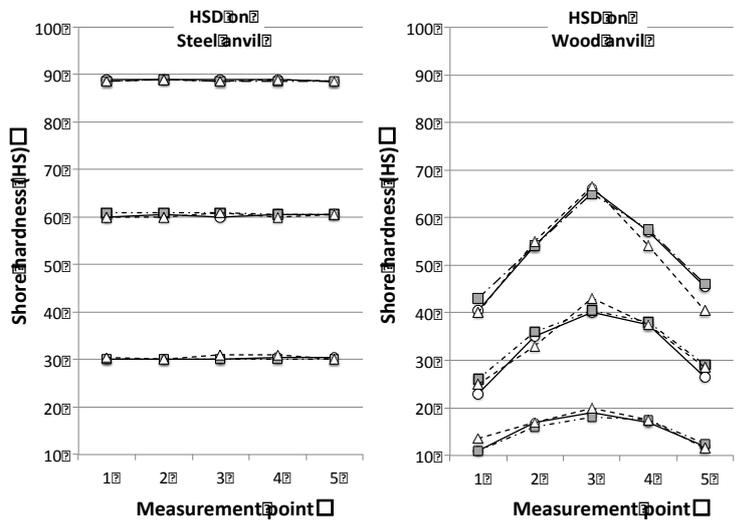


Fig. 7 Shore hardness values of JIS HS standard blocks obtained with the HSD tester on steel and wood anvils

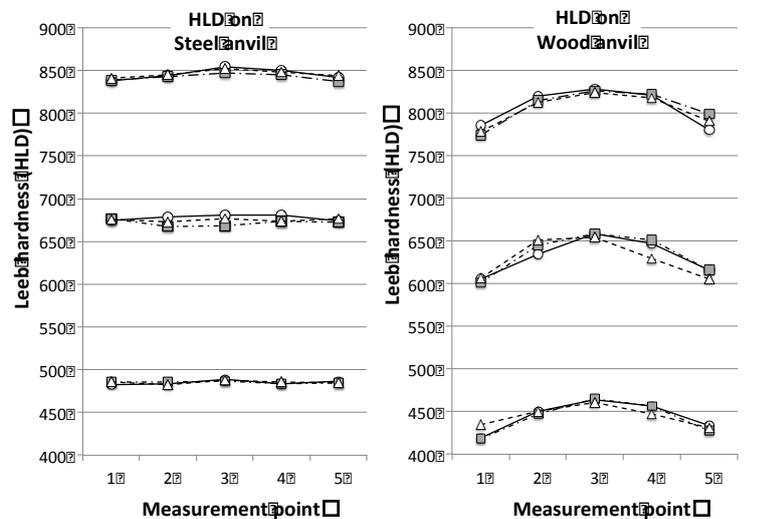


Fig. 8 Leeb hardness values of JIS HS standard blocks obtained with the HLD tester on steel and wood anvils

steel anvil by around 30 HLD at the block's center and around 60 HLD at close to the edge.

#### 4. CONSIDERATION

##### 4.1 Selection of the steel anvil

Because the selection of anvils is important for this experiment, we conducted preliminary tests to determine it. Specifically, we compared the results of HSD and HLD tests for three cases: (a) The specimen is set on the anvil for the Shore hardness tester mentioned above; (b) The specimen is set on two steel blocks (one weighing 2.7 kg stacked on another weighting 4.6 kg); and (c) The specimen is set on the steel blocks described in the (b) above so that the specimen adheres firmly on top of the blocks by applying the coupling paste for Leeb harness on the specimen's bottom surface. As a result, it was revealed that these conventional rebound hardness testers produced remarkably lower and variable hardness measurements in the case of (b), compared with (a) and (c). Regarding the case of (c), the status of application of the coupling paste and its adhesion to the blocks can have an effect on the test results. Accordingly, we selected the steel anvil as described in the (a) above for the experiment in this research, because it was expected to cause the least mass effect.

##### 4.2 Position of tester relative to center of wood anvil

To best detect the mass effect in a rebound hardness test, it is desirable to conduct the test by ejecting a ball indenter or impact body vertically upwards to an inverted specimen with its bottom face being not in contact with anything, as described in research conducted by Nakamura and Maki, et al. [3] However, upward ejection is impossible with the HSD tester. Therefore, for this experiment, we decided to use the downward impacting direction for all testers, and employ the aforementioned wood anvil on the assumption that an office desk or similar weak wooden structure tends to be substituted for an anvil on site for practical reasons.

From the results of testing a small specimen with the conventional rebound hardness testers using the wood anvil, it was found that the specimen's edge effect, as well as its mass effect, appeared prominently according to the mass, strength, and/or size of the anvil. The test was conducted, ensuring that the test point of the specimen was at the center of the anvil, as shown in Fig. 9, because preliminary testing revealed that hardness measured at the same test point of the specimen was lower when it was at the periphery of the anvil.

This suggests that one should note the edge effect of the anvil, in addition to the specimen's mass and edge effects when conducting conventional rebound hardness tests [8].

##### 4.3 Comparison of mass effect among the rebound hardness tests examined

To compare the mass effect among the three testers examined in a uniform manner, it is necessary to convert the Shore and Leeb hardness values shown in Figs. 6 – 8 into coefficient of restitution  $e$ , an indicator of hardness for the HNM-2012 tester. This conversion was made using the equations:  $e = \sqrt{HS/140}$  and  $e = HLD/1000$ .

Mass effect was compared among the HNM-2012, HSD, and HLD testers by obtaining the coefficient of restitution  $e$



Fig. 9 Testing specimen at the center of anvil.

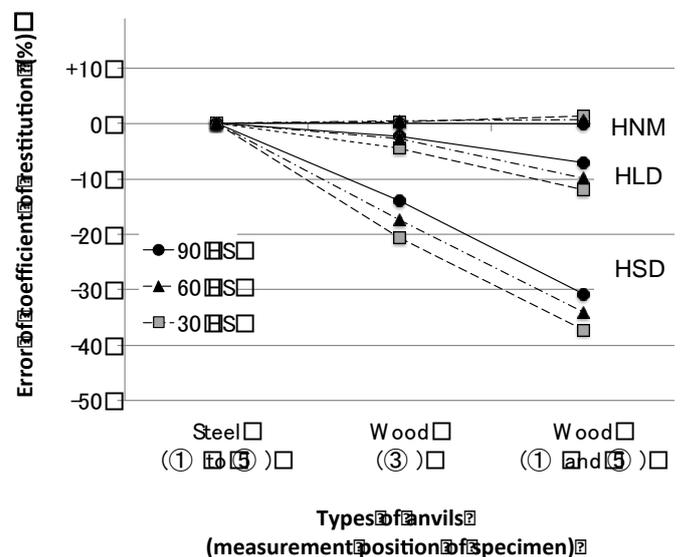


Fig. 10 Error of coefficient of restitution of JIS HS standard blocks demonstrated by wood anvil.

for the steel and wood anvils. For the steel anvil, the average of measurements at the five positions ① through ⑤ in Fig. 4 was used to calculate the coefficient. For the wood anvil, measurements at test point ③ in Fig. 4, which is at the center of the specimen, and test points ① and ⑤ in Fig. 4, which are close to the periphery of the specimen, were used to obtain the respective coefficients of restitution and their difference from the coefficient of restitution for the steel anvil. The results are shown in Fig. 10, which clearly indicate the existence of a mass effect with conventional testers, but not the HNM-2012 small ball rebound hardness tester.

## 5. CONCLUSION

- (1) By making the prototype HNM-2012 tester, it was confirmed that the material and testing direction of a 3-mm small ball can be freely selected.
- (2) No mass and edge effects of the JIS-compliant Shore hardness block used as a specimen were observed with the HNM-2012 tester, even when the test was carried out on a wood anvil by having a 3-mm diameter alumina ball impact the specimen at a velocity of about 10 m/s.
- (3) With conventional rebound hardness testers, or HSD and HLD testers, for which a hammer or an impact body is used to hold an indenter when it strikes the specimen, the specimen's mass effect was observed with lower hardness measurements when tested on the wood anvil compared to the steel anvil.
- (4) In addition, the conventional testers used with the wood anvil also showed an edge effect with the specimen; i.e., hardness measurements at points closer to the periphery of the specimen tend to be lower than those at the center of the specimen.
- (5) The mass and edge effects observed with the conventional testers are only detectable through a careful comparison with the results of a test on a specimen that ideally adheres to a large anvil. In practice, however, it is suspected that a specimen's hardness values and distribution can be incorrectly determined on a daily basis in the industrial field.
- (6) If the small ball rebound hardness test method discussed here, or the HNM method, is employed for onsite rebound hardness testing for industrial purposes, it would help provide an easier method enabling onsite testing of the rebound hardness of a specimen that is equal to or smaller than the size of JIS-compliant Shore hardness reference blocks. In addition, the method is expected to provide an easy table-top means of testing normally sized reference blocks, as an essential tool for managing the accuracy of hardness testing machines.
- (7) In the future it will be necessary to discuss the lowest possible weight of test specimen that poses no mass effect when tested with the HNM method under different testing conditions as to material, size, mass and ejection velocity of the ball indenter.
- (8) Although not the purpose of this research, we confirmed that applying the JIS Shore hardness testing machine frame for the Leeb hardness tester eliminates the need for coupling paste, thereby enhancing the test's reliability and ease of operation, even when a small specimen has to be tested for unavoidable reasons.

Besides the mass effect, the HNM method also has several advantages over conventional rebound hardness tests, including high geometrical accuracy and interchangeability of indenters, and no need to embed the indenter in the impact body or make adjustments.

## REFERENCES

- [1] Masaki Koga, "Historical Development of Material Hardness Testing Technologies," Survey Reports on

- the Systemization of Technologies, National Museum of Nature and Science, Vol. 14, p. 12 (2009)
- [2] Takashi Yamamoto, "Development of Hardness Testing and Consensus-building of Hardness by Standard Blocks for Hardness in Japan," Heat Treatment, Vol. 51, No. 6, p.323 (2011)
- [3] Masao Nakamura, Seiji Maki and Koji Sasamoto, "Impact Hardness Testing Method" Journal of Material Testing Research Association of Japan, Vol. 32, No.1, p. 24 (1987)
- [4] M. Yamamoto, T. Yamamoto, M. Urada, K. Miyahara, S. Maki and M. Nakamura, "Proof Examination on Small Rebound Hardness Carried out with HLD/HLE Standard Blocks," Journal of Material Testing Research Association of Japan, Vol. 56, No.4, p.185 (2011)
- [5] JIS B 7727: 2000 Shore hardness test – Verification of testing machines
- [6] D. Leeb and H.A. Kalt (Japanese translation by Tadanobu Kashiwa), "Conversion Problems with Hardness Values of Rolls," Journal of Material Testing Research Association of Japan, Vol. 33, No.3, p.187 (1988)
- [7] JIS B 7731: 2000 Shore hardness test – Calibration of reference blocks
- [8] Takeo Yoshizawa, Hardness Test Methods And Their applications, Shokabo publishing co., ltd., P.116, 143 and 147 (1967)