TECHNICAL ARTICLE

Hardness Measurement for Metals Using Lightweight Herbert Pendulum Hardness Tester With Cylindrical Indenter

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Abstract

A Herbert pendulum was modified to a lightweight pendulum with a cylindrical indenter by Habara in order to measure the hardness of viscoelastic materials such as plastics and rubbers. It is difficult to provide enough strain to evaluate the hardness of hard materials using the Herbert pendulum with a cylindrical indenter because the contact stress between the indenter and the specimen is smaller than that of the original Herbert pendulum. In this study, a modified measurement system is developed to accurately measure the swing angle of a lightweight Herbert pendulum with a cylindrical indenter. Two independent laser displacement meters are installed, to provide a noncontact measurement of the swing angle. The modified Herbert pendulum with a cylindrical indenter is evaluated for measuring the hardness of metals. Four types of Herbert hardness are compared with the Vickers hardness. Good correlation is shown between the damping hardness (one type of Herbert hardness) and the Vickers hardness. The damping hardness measured based on the modified Herbert hardness tester can be used as the hardness parameter of the metals.

Introduction

Hardness measurement tests for metals can be roughly categorized into two types: indentation test[1] and rebound test.[2] In indentation hardness test, an indenter is impacted onto the material being tested. The indentation hardness can be calculated from the load and the impression area. In rebound hardness test, a hammer is dropped from a fixed height onto the surface of the test material. The rebound hardness can be calculated from the rebounding height of the hammer measured after the first contact.

A pendulum hardness test is different from both the indentation hardness and the rebound hardness tests. A pendulum with an indenter as the fulcrum is swung on a specimen, and the attenuation behavior of the specimen is measured. The attenuation behavior varies with the hardness of the specimen because the rolling resistance of the indenter on the specimen is dependent on the hardness. Some pendulum hardness tests were proposed to measure the hardness of materials such as metals,[3] woods,[4] and viscoelastic materials.[5] Persoz and König pendulum hardness testers are commonly used for measuring the hardness of coatings and films.[5]

The original Herbert pendulum hardness tester (Fig. 1) was developed by Herbert[3] in 1923. The tester is an inverted pendulum-type tester and has a spherical indenter as the fulcrum and can be used to measure relatively high-hardness materials (compared with the indenter material). The original Herbert pendulum is made from steel and weighs about 4 kg. The indenter is of a diamond sphere with a 2 mm diameter. The swing angle of the pendulum can be measured using a level gage mounted to the pendulum. The Herbert hardness tester is effective for measuring the hardness at specific locations such as the edge of a drill bit. The Herbert hardness measures four types of hardness (Fig. 2):

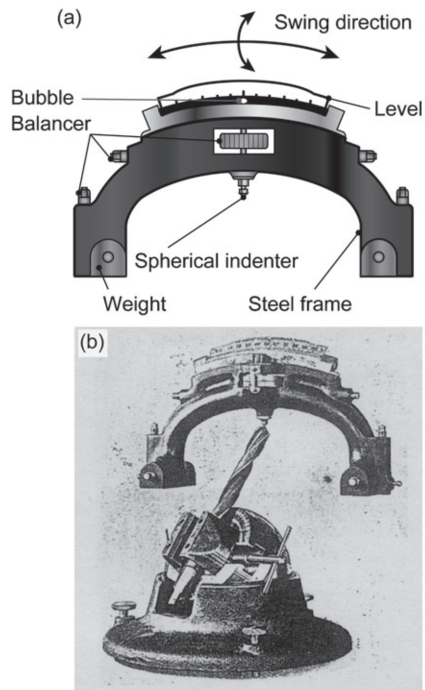

Figure 1 Schematic illustration (a) and photograph (b) of the original Herbert pendulum.

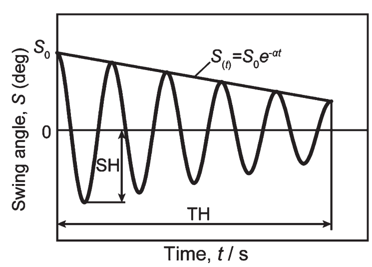

Figure 2 Schematic diagram of an attenuation curve and the definition of Herbert hardness.

1. The scale hardness (SH) is the first swing angle.
2. The time hardness (TH) is the time for 10 swings of the pendulum.
3. The flow hardness (FH) is defined as SH/TH.
4. The damping hardness (DH) is the damping coefficient.

The first three types of hardness were defined by Herbert. The SH has little effect due to work hardening, while the TH includes some effect due to work hardening. As one of the common hardness tests, the Brinell hardness (HBW) includes some effect due to work hardening. The relationship between the TH and the HBW can be expressed as[6]:

$$\mathrm{TH} = 1.7\mathrm{HBW}^{\frac{1}{2}} + 0.000047\mathrm{HBW}^2 \quad (1)$$

The DH is the damping coefficient, α, of the envelope curve for the attenuation oscillation (Fig. 2). The swing angle, $S(t)$, of the pendulum can be expressed as:

$$S_{(t)} = S_0 \mathrm{e}^{-\alpha t} \quad (2)$$

where t is time, and S_0 is the initial angle of the pendulum. The DH defined by Matsubara[7] decreases with an increase of the hardness of the specimen. The DH includes the effect due to work hardening.

The Herbert pendulum was modified to a lightweight pendulum with a cylindrical indenter by Habara,[8] as shown in Fig. 3, to measure the hardness of viscoelastic materials such as plastics and rubbers. The Habara-type Herbert pendulum swings two-dimensionally because the pendulum has a cylindrical indenter. On the other hand, the original Herbert pendulum swings three-dimensionally because the pendulum has a spherical indenter. The swing angle for Habara-type Herbert pendulum is measured using a protractor mounted on the tester. The attenuation behavior of the Habara-type Herbert pendulum with a cylindrical indenter can be measured more accurately than the original Herbert pendulum. This is because two-dimensional swing can be more accurately detected by the protractor than three-dimensional swing. However, correlation was not found between the Herbert hardness and the durometer hardness, which is widely used as the hardness criterion for plastics and rubbers. Recently, Matsubara[9] mounted a potentiometer to the Herbert pendulum with a cylindrical indenter in order to measure the swing angle electronically as shown in Fig. 4. The Matsubara-type Herbert pendulum is made from aluminum alloy with mass about 1.5 kg. The indenter is cemented with carbide cylinders with 2 to 8 mm in radius. The hardnesses of various plastics were measured, and the correlation between the Herbert hardness and the durometer hardness was identified. The potentiometer has two negative effects on the swing of the pendulum although the swing angle can be measured electrically.

1. The position of the center of gravity of the pendulum changes during swinging because an anchor-shape weight attached to the potentiometer does not swing.
2. The stiffness of lead wires of the potentiometer prevents the swing of the pendulum.

The Matsubara-type Herbert pendulum may be further improved.

The Herbert pendulum with a cylindrical indenter is able to measure a wide range of hardnesses. However, it is difficult to provide enough strain

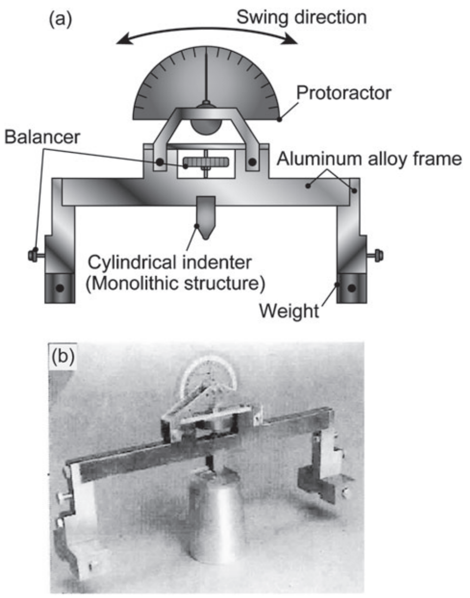

Figure 3 Schematic illustration (a) and photograph (b) of the Habara-type Herbert pendulum.

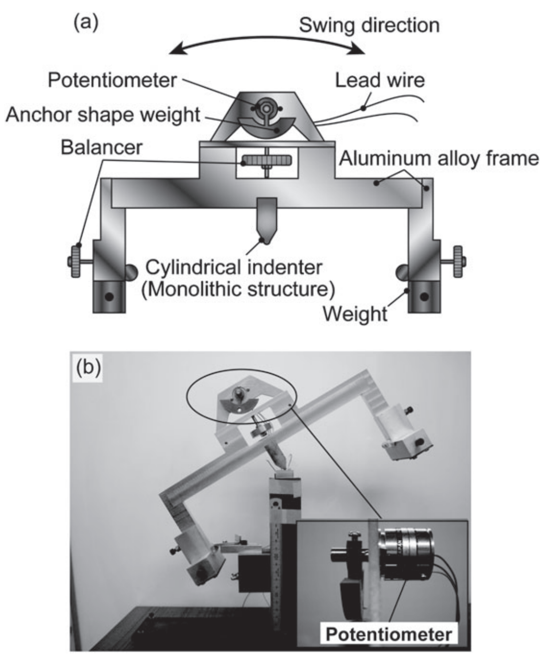

Figure 4 Schematic illustration (a) and photograph (b) of the Matsubara-type Herbert pendulum.

to evaluate the hardness of hard materials using the Herbert pendulum with a cylindrical indenter because the contact stress between the indenter and the specimen is smaller than that of the original Herbert pendulum. In this study, we modify the Matsubara-type Herbert pendulum hardness tester to enable noncontact measurement of the swing angle to improve the accuracy. The use of the lightweight Herbert pendulum with a cylindrical indenter is evaluated by measuring the hardness of various metals.

Modified Herbert Pendulum Hardness Tester

A schematic diagram and a photograph of the modified Herbert pendulum are shown in Fig. 5. The modified Herbert pendulum is composed of an A5052 aluminum alloy frame, a steel reflective plate, a steel indenter holder, a carbide indenter, and brass weights. The reflective plate is mounted on the pendulum in order to reflect a laser beam from a laser displacement meter. The swing of the modified Herbert pendulum is not affected by the new swing angle measurement system because it can provide the noncontact measurement of the swing angle. The indenter of the Matsubara-type Herbert pendulum has a complex shape because it has monolithic structure of the attachment part and the indenter tip. It is difficult to accurately manufacture the indenter with a complex shape. In the modified Herbert pendulum, the indenter is a carbide cylinder with a radius of 1 mm and a length of 12 mm. The highly accurate indenter can be manufactured quite easily because of the simple shape of the indenter. The indenter holder is manufactured as the attachment part. It is isolated from the indenter. The indenter is shrinkage-fit to the indenter holder and attached to the aluminum frame. The monolithic body frame is adopted instead of an assembled body frame in order to reduce the effect of the assembly accuracy on the swing of the pendulum. The balancer weights on the center and both sides of the modified Herbert pendulum can be moved by screw to adjust the position of the center of gravity of the pendulum.

A schematic diagram of the modified Herbert pendulum hardness testing system is shown in Fig. 6. Two laser displacement meters were installed, independent from the modified Herbert pendulum, to provide a noncontact measurement of the swing angle. A reflective plate was attached to the top of the modified Herbert pendulum. The vertical position of the laser displacement meters can be changed to accommodate various thicknesses of the specimen. The lasers irradiate the reflective plate attached to the modified Herbert pendulum, and the displacement data is recorded by a PC while the pendulum swinging. The swing angle, θ, is expressed using the difference, ΔL, between the displacements

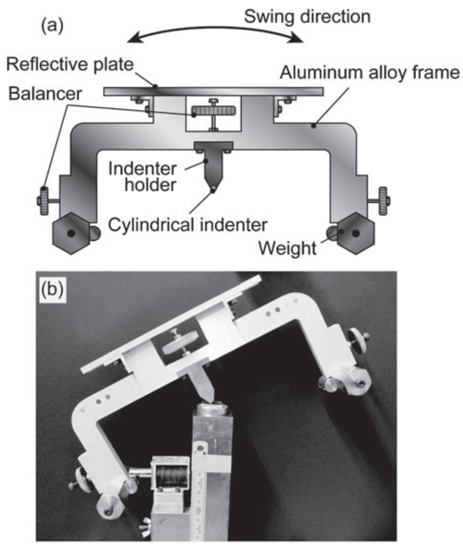

Figure 5 Schematic illustration (a) and photograph (b) of the improved Herbert pendulum.

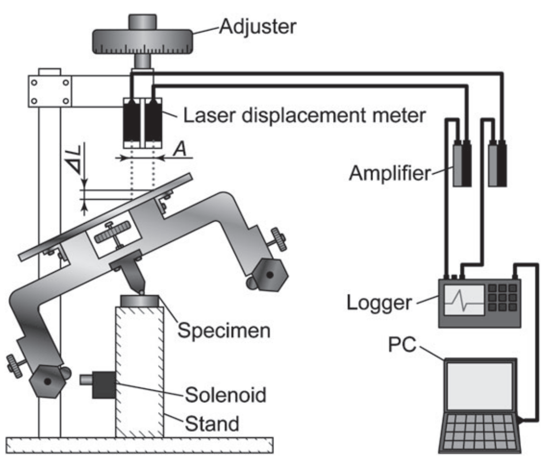

Figure 6 Modified Herbert hardness testing system.

measured by the laser displacement meters,

$$\theta = \tan^{-1} \frac{\Delta L}{A} \quad (3)$$

where A is the distance between the two laser beam positions, 35.25 mm. The modified Herbert pendulum is released from the initial position by the release system using a solenoid.

Calibration of the Herbert Pendulum

The mean swing cycle of the pendulum on the sapphire was adjusted to 20 s before the Herbert hardness test. The swing cycle adjustment was performed with the following procedures (Fig. 7).

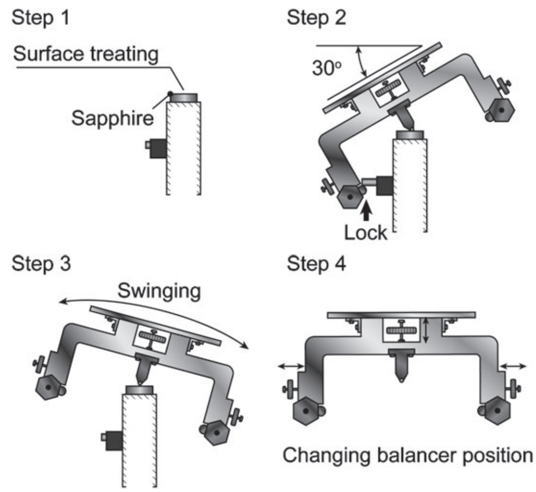

Figure 7 Calibration process of the Herbert pendulum.

1. The sapphire circular plate as a standard sample was surface treated with acetone and was dried.
2. The pendulum was fixed at an initial angle of $\theta = 30^{\circ}$ using the solenoid on the sapphire.
3. The pendulum was released from the solenoid, and then swung 10 cycles. The swing angle was measured during the swinging the pendulum.
4. The position of the center of gravity of the pendulum was adjusted using the balancer weights when the mean swing cycle is not 20 s.

Finally, the mean swing cycle was adjusted to 20 s by repeating the procedures 1–4.

Hardness Test

Brinell standard hardness blocks (HBW150, 300, 450, and 600), SPCE, SS400, SUS304, SUS430, and A1050 aluminum alloy were used as the specimens. The elastic moduli and Poisson's ratios of the specimens are listed in Table 1.[10–19] The maximum contact stress, P_H, calculated using Hertz's contact theory is also listed in Table 1. HBW150 is S45C, and HBW300, 450, and 600 are SK85 (SK5). The hardnesses of HBW300, 450, and 600 were adjusted by heat treatment. The same elastic parameters are used for the calculation of the maximum contact stress of HBW300, 450, and 600 because the elastic moduli and Poisson's ratios are structure insensitive. The hardness test procedures are similar to the calibration of the Herbert pendulum and are given below.

Step 1. The surfaces of the specimens were polished with emery paper up to a 1200 grade and treated with acetone.

Table 1 Elastic parameters of indenter and specimens and Hertz contact stress

	Young's modulus (GPa)	Poisson's ratio —	P_H (MPa)
Ceramic carbide	540	0.22	—
HBW600 (SK5) HBW450 (SK5) HBW300 (SK5)	206	0.30	253
HBW150 (S45C)	211	0.29	255
SUS430	240	0.16	260
SUS304	192	0.29	246
SPCE	198	0.33	251
SS400	209	0.29	254
A1050	68	0.30	162

Table 2 Hardnesses and yield strengths of the specimens

	TH	SH	FH	DH × 10^{-3}	HV	Yield stress (MPa)
HBW600 (SK5)	99.6	28.7	0.288	0.571	644	1932
HBW450 (SK5)	99.6	28.6	0.287	0.699	480	1440
HBW300 (SK5)	99.2	28.0	0.282	0.922	328	984
HBW150 (S45C)	99.2	27.1	0.273	1.55	159	477
SUS430	99.7	27.6	0.276	1.63	181	543
SUS304	99.7	27.2	0.272	1.77	190	570
SPCE	98.5	24.5	0.249	9.41	93.7	281
SS400	94.2	26.1	0.280	2.54	106	318
A1050	84.8	20.7	0.246	23.0	22.3	66.9

Step 2. The pendulum was placed on the specimen and fixed with an initial angle $\theta = 30^\circ$ using the solenoid.

Step 3. The pendulum was released from the solenoid and then swung 10 cycles. The swing angle was measured during swinging the pendulum.

The data analysis was performed with the following procedures:

1. The moving average of the swing angle, S_{MA}, is calculated from the previous four data points and the current data point.

$$S_{MAn} = \frac{1}{5}\sum_{n-4}^{n} \theta_i \, (n \geq 5) \tag{4}$$

2. The local maximum and the local minimum swing angles are obtained from the moving averaged swing angle.
3. The absolute initial local minimum swing angle is the SH and the TH is the time at the fifth local maximum swing angle. The flow hardness is obtained by dividing the SH by the TH.
4. The envelope curve for the attenuation curve is obtained by plotting the local maximum swing angles against the time.
5. The DH, α, is the slope of the natural logarithmic local maximum swing angle-time curve and calculated using least-squares method.

The Vickers hardness test, as the most common hardness test for metals, was also performed on all specimens for comparison with the Herbert hardness.

Results and Discussions

The Vickers hardnesses of the specimens are given in Table 2. Based on the results of the Vickers hardness test, HBW600 is the hardest material among the specimens tested, while A1050 aluminum alloy is the softest material. The attenuation curves of HBW600 and A1050 aluminum alloy in the Herbert hardness test are shown in Fig. 8. The swing decayed little for HBW600 after 10 swings. On the other hand, the swing decayed to 4.5° for A1050 aluminum alloy after 10 swings. The resistance force from a low-hardness material to the indenter is higher than that from a high-hardness material. The mechanical energy of the pendulum is decreased as a result of resistance force. Thus, the swing strongly decayed for A1050 aluminum alloy when compared with that of HBW600.

The swing cycles of all the specimens (by number of swings) are listed in Table 3. The swing cycle of A1050 aluminum alloy decreased with an increase in the number of swings. On the other hand, the swing cycle for the specimens without A1050 aluminum alloy did not change with an increase in the number of swings. The yield strength, σ_y, is expressed as a function of the Vickers hardness, HV.[20]

$$\sigma_y \approx 3\text{HV} \tag{5}$$

The calculated yield strengths of all of the specimens are listed in Table 2. Only the maximum contact stress of A1050 aluminum alloy is higher than the corresponding yield strength. Surface micrographs of HBW600 and A1050 aluminum alloy after the Herbert hardness tests are shown in Fig. 9. The A1050 aluminum alloy yielded because an impression line was observed on its surface. On the other hand, no impression line was observed on the surface of the HBW600. A clear impression was observed on the specimen surface after the hardness test using the original Herbert pendulum.[3] Fox[21] discussed the energy absorption mechanisms in the pendulum hardness testing of glass and reported that

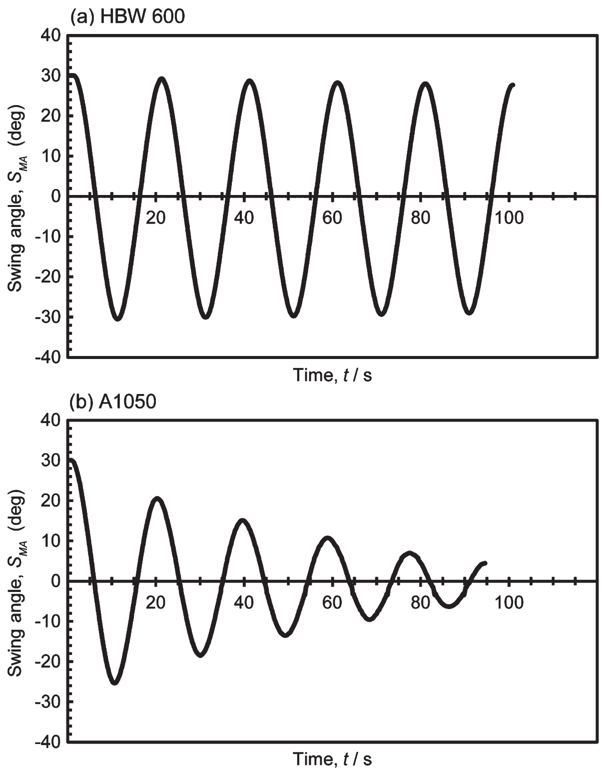

Figure 8 Attenuation behaviors for (a) HBW600 and (b) A1050.

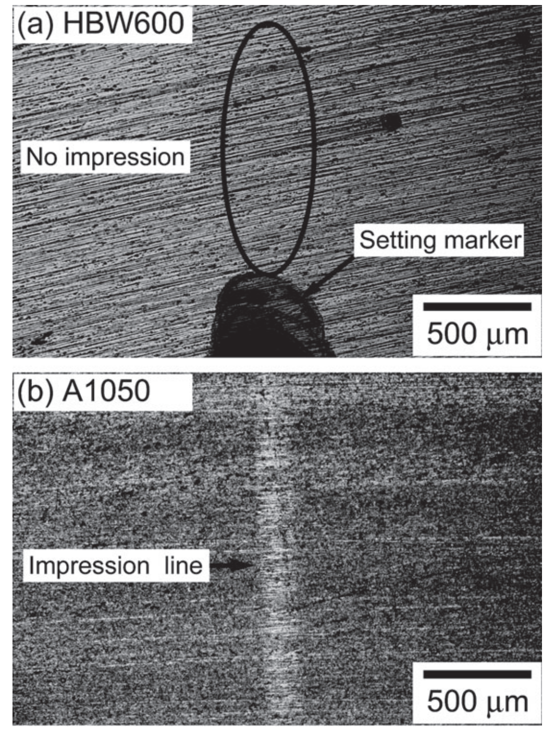

Figure 9 Photographs of the surface of HBW600 steel and A1050 aluminum alloy after the Herbert hardness test.

Table 3 Change of the swing cycle during Herbert hardness test

	Cycle number				
	1	2	3	4	5
HBW600	20	19.9	19.9	19.9	19.9
HBW450	19.9	19.9	19.8	19.9	19.8
HBW300	19.9	19.8	19.9	19.8	19.9
HBW150	19.8	19.8	19.8	19.8	19.8
SUS430	20	20	20	19.9	20
SUS304	19.9	20	19.9	20	19.9
SPCE	19.9	19.8	19.7	19.6	19.6
SS400	19.8	19.9	19.9	19.9	20
A1050	19.4	19.3	18.6	17.2	15.6

the attenuation of the pendulum is caused mainly by energy absorption due to plastic deformation. An impression was clearly observed by microscope for the glass. In the case of $P_H > \sigma_Y$, the swing cycle decreases during swinging because the mechanical energy dissipates due to the plastic deformation.

The SH and TH are plotted against the Vickers hardness in Fig. 10(a) and (b), respectively. The SH was evaluated using the second swing angle because some of the first swing angles were higher than the initial swing angle. This overshoot was caused by the distance between the ideal and the actual centers of gravity of the modified Herbert pendulum and the slip between the indenter and the specimen.

The SH and TH increased with an increase in the Vickers hardness to HV100. The SH and TH determined using the original Herbert pendulum are also plotted against the HBW in the same figures.[6] The measurement principle of the Vickers hardness is similar to that of the HBW, although the indenter material and shape are different. The HBW is close to the Vickers hardness with about 5% lower. The SH determined by the original Herbert pendulum monotonically increased with an increase in the HBW. The TH determined using the original Herbert pendulum also monotonically increased with an increase in the HBW. The TH determined by Habara[8] has large dispersion. The TH and SH determined form the original Herbert pendulum can be used as a hardness parameter for metals. However, none of them determined from the modified Herbert pendulum can be used as a hardness parameter.

The flow hardness and DH are plotted on a double logarithmic scale against the Vickers hardness in Fig. 11. The flow hardness determined by the original Herbert pendulum is also plotted against the HBW in the same diagram. The flow hardness measured

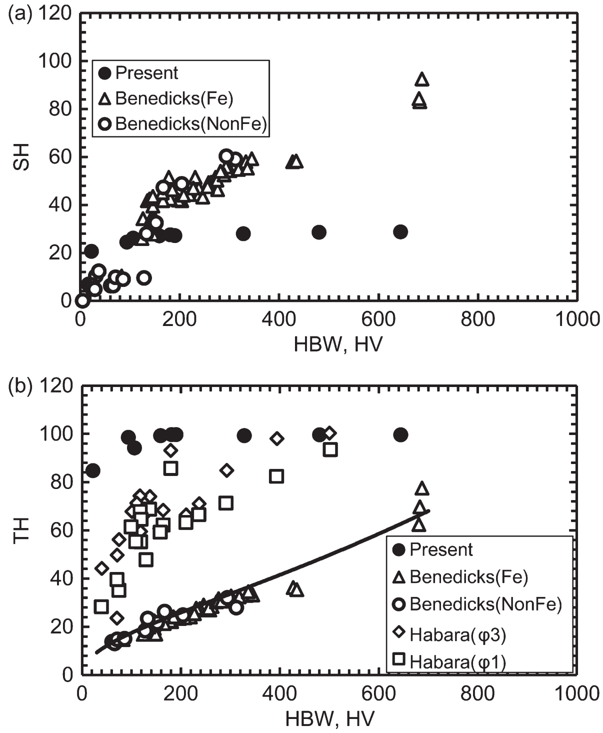

Figure 10 The scale hardness (a) and time hardness (b) plotted against the Vickers hardness or Brinell hardness.

in the present study varied little with an increase in the Vickers hardness. The flow hardness measured by Benedicks[6] increased with an increase in the HBW to HBW180 and then gradually decreased. On the other hand, the DH decreased almost monotonically with an increase in the Vickers hardness. The DH proposed by Matsubara can be used as a hardness parameter for metals, although the flow hardness cannot be used. The hardness of metals could be evaluated using the lightweight Hebert hardness pendulum with a cylindrical indenter. The relationship between the DH and the Vickers hardness can be expressed as:

$$DH = 0.824 HV^{-1.16} \tag{6}$$

In the present study, the specimen was slightly plastically deformed because the maximum contact stress between the indenter and the specimen without A1050 aluminum alloy was smaller than the yield stress. The DHs of HBW300, 450, and 600 decreased with an increase in Vickers hardness, although the specimens were made from the same material (SK5) with the same elastic properties. The Herbert pendulum can detect differences in internal friction in aluminum alloy.[22] The internal friction has been widely used to evaluate the damping performance of metals and can be measured without the plastic

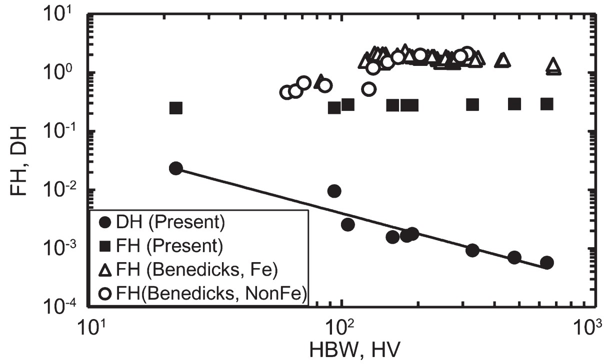

Figure 11 The damping hardness and flow hardness plotted against the Vickers hardness or Brinell hardness.

deformation of the specimen.[23] The attenuation of the modified Hebert pendulum can be caused by the elastic and plastic deformations. It can also be caused by the internal friction. The modified Herbert hardness tester can also be used as a simple evaluation method for damping properties.

Conclusions

In this study, Herbert hardness tester was modified to more accurately measure the swing angle. Some hardness tests were performed for some metals, and the associated Herbert hardness was compared with the Vickers hardness. The following conclusions were obtained in the study:

1. The TH, the SH, and the flow hardness obtained from the lightweight Herbert pendulum are inappropriate for use as a hardness parameter for metals because these harnesses change little with an increase in the Vickers hardness.
2. Good correlation is shown between the DH and the Vickers hardness. The modified Herbert pendulum can measure the hardness of metals using the DH as the hardness criterion.
3. The attenuation of the modified Hebert pendulum can be caused by elastic and plastic deformations and by internal friction.

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