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TECHNICAL ISSUES RELATED TO ISO HARDNESS TEST STANDARDS

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Abstract – The ISO standards for hardness tests, including Rockwell, Vickers and Brinell, have become bloated, compelling users of the standards to pay an excessive amount of attention and cost to comply with them. In essence, good standards should be simple and clear. Experts on hardness tests and creators of standards should give more consideration when making such standards.

From this standpoint, as a manufacturer specializing in the production of hardness test blocks, we present some issues to be improved concerning relatively recent hardness test standards based on theoretical considerations and experimental facts.

Keywords: Hardness, Standard blocks, ISO, Indenter, Force

1. STATIC INDENTATION HARDNESS TESTS

1.1. Loading Conditions

The loading conditions of static indentation hardness tests are basically defined by two elements: load rising time (“LRT”), or the time taken for the load to reach the full test force, and load duration time (“LDT”), or the period during which the full test force is applied. Hardness values indicated by a hardness test block vary according to LRT and LDT. Fig. 1 shows the hardness values obtained with a 700HV steel Vickers test block when LRT was changed significantly between 1 and 100 seconds under six loads. This result shows that the value of Vickers hardness changed with the value of LRT. Looking at this result from a different perspective, you can see that the indenter penetration speed (μm/s) does not affect hardness values if LRT remains the same. This means that what is important for defining the loading speed is LRT, not indenter penetration speed (μm/s).

Regarding LDT, as shown in Fig. 2, an extended load duration resulted in lower hardness values for either test block made of copper alloy, steel, or ceramic. These test results show that, even when the same test force is applied, changing LRT or LDT causes a change in the block material’s resistance to deformation. Therefore, defining loading conditions too strictly can only result in the difficulty obtaining a constant hardness value unique to the material of a test block.

In essence, a hardness test block is a standard test piece designed to determine the acceptability of hardness tests under generally used testing conditions. Therefore, the standard hardness value indicated on a test block must be obtained by testing it under general testing conditions.

In contrast, the loading conditions prescribed in the ISO test block standards for Brinell and Vickers hardness tend to

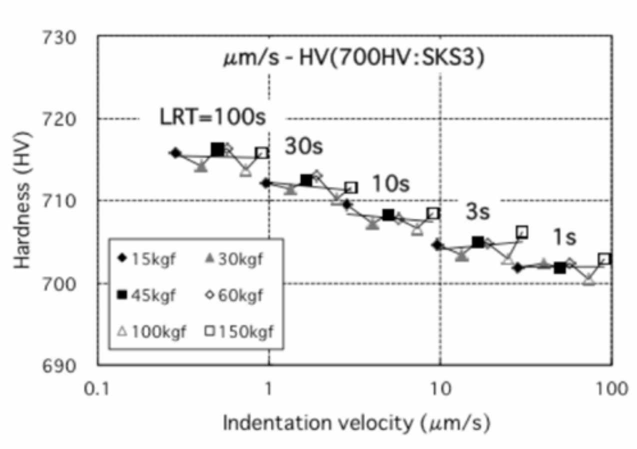

Fig. 1 Changes in Vickers hardness values of steel test blocks according to LRT

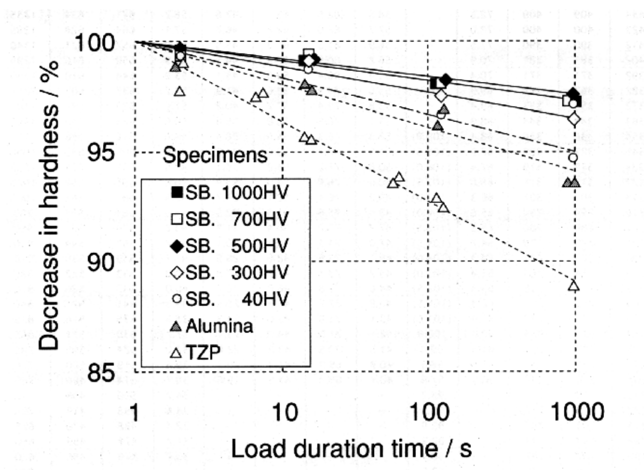

Fig. 2 Changes in Vickers hardness values of steel and copper alloy test blokcs and ceramic specimens according to LDT

deviate from the standard conditions specified in the test method standards. This tendency seems to suggest some reasons behind it. They might be trying to achieve any fixed hardness value for a given test block material, which does not exist in practice. Or they might adhere to the testing conditions they have traditionally applied. Given the *raison d’etre* of a hardness test block, however, this is like not seeing the forest for the trees, and such test block standards must be reviewed. Providing convenience to the creators of standards at the expense of the intention of the users of standards must be avoided.

1.2. Test Force

In indentation hardness tests, a difference in the indentation test force applied automatically translates into a difference in the measured dimensions of an indentation generated, which then leads to an error in the hardness value of the tested material. Therefore, ISO test block standards (Part 3) for Rockwell, Vickers, and Brinell hardness tests require a strict tolerance of up to 0.1% for test forces applied by the testing machines used to determine the standard hardness values for these hardness tests. This error range is about one tenth of the tolerable error range for the test forces applied by hardness testing machines generally used in the industrial world.

Due to the difficulty of verifying the accuracy of dynamic loading, current standards prescribe the method for verifying static loading for convenience. However, you should note that a hardness testing machine with excellent static loading accuracy does not always have equally excellent dynamic loading accuracy.

Regarding the preliminary test forces for Rockwell hardness testing, an equally strict error tolerance of up to 0.2% is specified for either the 1st preliminary force before the total test force is applied or the 2nd preliminary force after it is applied. However, the load vs. displacement curve for metallic specimens, as shown in Fig. 3, has significantly different slopes between when the load is being applied and when it is being removed. The curve also suggests that the preliminary force error after the total test force is applied (the broken line in the figure) does not cause a large error in the displacement (b≪a). The same fact is also suggested by Fig. 4, which shows the result of an experiment carried out by testing the hardness blocks between 10 HRC and 70 HRC using the 1st and 2nd preliminary forces with varying errors. As these results suggest and considering the aforementioned nature of Rockwell hardness testing, there is ample room for relaxing the tolerable range of preliminary force error after the total test force is applied. With the current limitation on verifying the accuracy of dynamic loading also taken into account, unnecessarily strict requirements could hinder the sound use of hardness tests[1].

1.3. Indenter Geometry

Errors in the geometry of the spherical tip of an indenter used for indentation hardness testing have different effects on hardness values according to the test method. Fig 5 shows a comparison of diameter, differential depth Δh, and maximum penetration depth h_{max} of indentations made on a hardness block under different test forces between a 120° cone indenter and a Rockwell diamond indenter with a spherical tip of 0.2 mm in radius of curvature. The comparison was made by showing the ratio of indentation dimensions obtained with a Rockwell diamond indenter to those obtained with a 120° cone indenter. The comparison of diameters (Fig. 5 (a)) suggests that test methods, including Vickers and Brinell hardness, in which an indentation in the surface of a specimen is measured optically are less subject to the geometry error of an indenter tip. In contrast, the comparison of maximum penetration depths (h_{max}, Fig. 5 (c)) suggests that test methods, including an instrumented indentation test, in which the depth of an indentation is measured, are much more vulnerable to such errors.

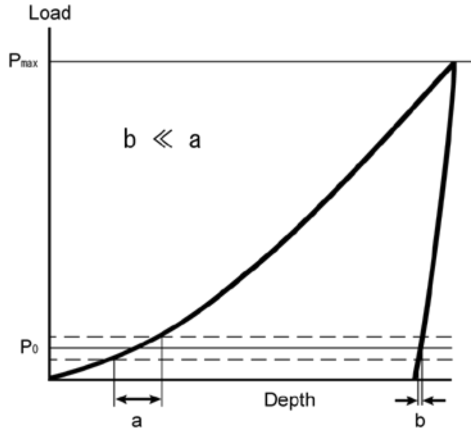

Fig. 3: Difference in slope of load-indentation depth curve of metals before the load is applied and removed (example of single crystal tungsten test blocks)

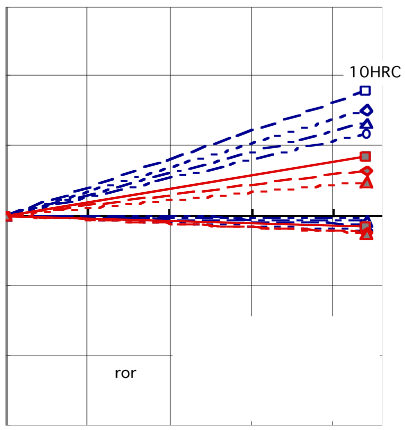

Fig. 4 Effects of errors of preliminary test forces before the total load is applied and removed for Rockwell C hardness testing

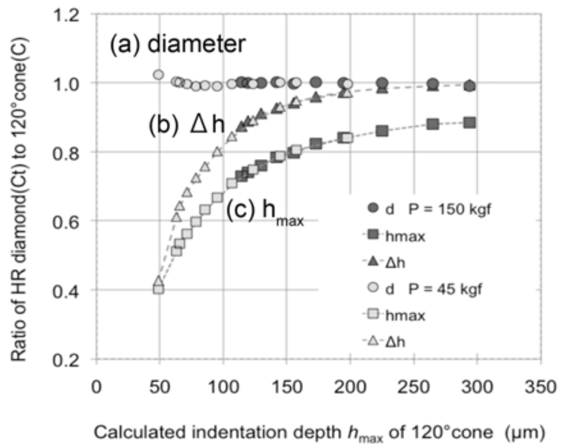

Fig. 5 Comparison of diameter, differential depth, and maximum penetration depth of an indentation made with a 120° cone and Rockwell diamond indenters

The Rockwell and equivalent indentation test methods, which feature measuring not the true indentation depth, but an increase in the depth of an indentation under a preliminary test force between the time before the total test force is applied

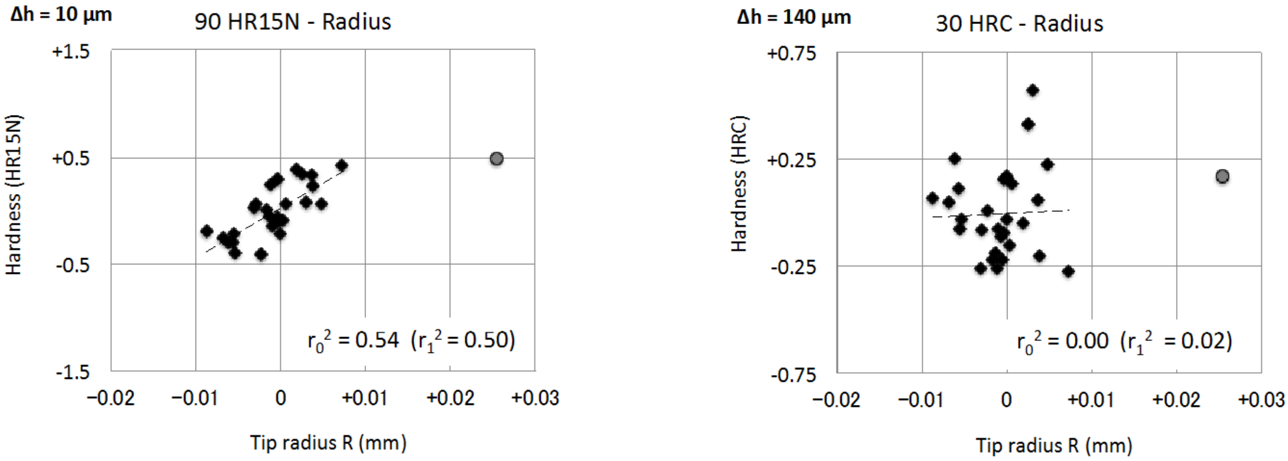

Fig. 6 Effects of indenter's tip radius R and cone angle errors on Rockwell HR15N hardness measurements

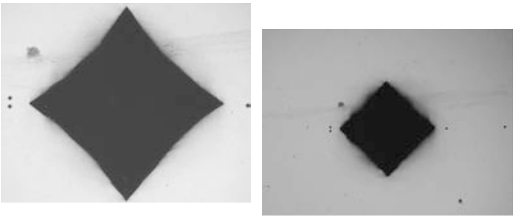

Fig. 7 Comparison of images of the same indentation in a pure copper 40 HV standard block taken with objective lenses of different magnifications

Automatically contrasted images taken with the 10x (left) and 5x (right) objective lenses

and the time after the total force is removed (differential depth), fall midway between (a) and (c) above (Fig. 5 (b)).

Due to the industrial significance of the Rockwell hardness test, there have been many discussions on the geometry of the spherical tip of a diamond indenter. From the result shown in Fig. 5, however, it is expected that the influence of the tip's geometry errors is limited to a hardness range with shallow indentations.

This expectation is supported by the result shown in Fig. 6, which compares the effects of the indenter tip's geometry errors on hardness test results between a 90 HR15N block for a Rockwell hardness range with shallow indentations and a 30 HRC block for a Rockwell hardness range with relatively deep indentations. From the figure it is found that hardness values do vary according to the tip radius for a hardness range of shallow indentations. Surprisingly, however, Rockwell hardness scales for a hardness range of relatively deep indentations, including HRC—which accounts for the largest portion of the Rockwell hardness range—are far less subject to the tip radius error as far as this experiment is concerned. Even for the 90HR15N hardness range with the shallowest indentations, the hardness value obtained with the indenter that has an error as large as 25 μm in tip curvature radius, or the value to the far right in Fig. 6, is not very different from those obtained with indenters that have errors as small as a few μm. This suggests that more important error factors than the geometry of indenter tip might be overlooked.

In terms of empirical facts, it must be recalled that in Rockwell hardness tests, ball indenters, which have much higher geometric accuracy than diamond indenters, tend to cause many more problems, such as variances of hardness values that are attributable to indenters. Considering these facts, it can be said that the current standards tend to be merely formalistically strict. Instead, we should turn our attention to more important aspects, such as the structure in which the diamond tip is mounted on the indenter shaft[2].

1.4. Microscopic Measurement of Indentations

When measuring an indentation in a test specimen, there is no established method for obtaining the true area of contact of the indenter, although many attempts to improve the device and technology for that purpose have been made. Unfortunately, the results of efforts to obtain the true dimensions of an indentation do not necessarily agree with those to improve the reproducibility of measuring the dimensions of an indentation.

Because the effort to obtain the true dimensions of an indentation tends to sacrifice ease of measuring an indentation, microscopic measurement of one Vickers indentation often requires a long time. Meanwhile, if you want to achieve higher measuring reproducibility and efficiency, you must prioritize ease of measurement for operator and sensor.

Fig. 7 shows microscopic images of the same Vickers indentation taken with objective lenses of different magnifications. The image to the left of an indentation taken with a 10x objective lens looks like a pincushion, whereas the image to the right of the same indentation taken with a 5x objective lens looks like a barrel. It should be remembered that microscopic images of a three-dimensional shape depend greatly on the conditions under which they are observed.

Fig. 8 shows the result when three operators (Opr 1-3) compared the dimensions of indentations of about 3 mm in diameter on 400 HBW10/3000 steel test blocks using four different commercially available indentation measuring microscopes for on-site use. Even this scale of experiment with a small number of operators ended with errors of ±2 % in hardness and ±1 % in diameter measurements [3]. Accordingly, we consider that the additional provision of the Brinell hardness testing machine standard, which requires that diameter measurements of reference indentations on a test block using on-site measuring microscopes agree within 0.5% from the standard value, must be promptly abolished [4].

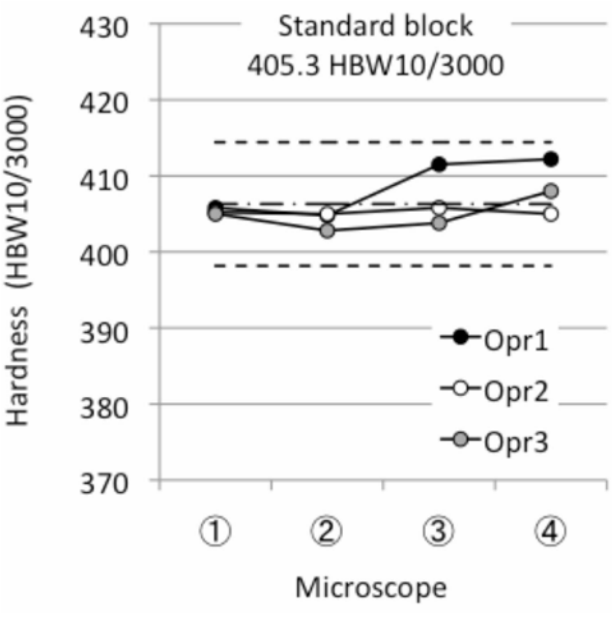

Fig. 8 Comparison of diameter of an indentation in steel hardness blocks measured with four commercially available Brinell indentation measuring microscopes

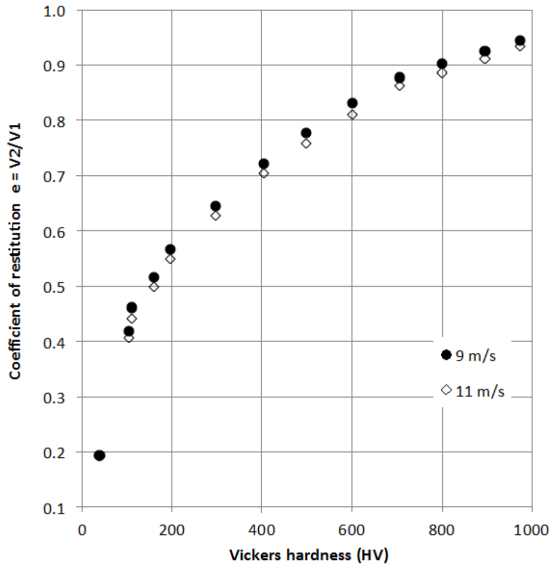

Fig. 9 Difference in coefficient of restitution caused by a difference of 20% in indenter ejection velocity when tested with copper alloy and steel hardness blocks using a three-millimeter alumina indenter for small ball rebound hardness (HNM) testing

2. REBOUND HARDNESS TEST

2.1. Mass Effect

In conventional rebound hardness tests, such as Shore and Leeb, an indenter embedded at the tip of a metallic hammer or impact body strikes the test specimen. Therefore, if the test specimen is small and light, the mass effect can cause errors in hardness measurements. To prevent that, the relevant JIS have some prescriptions: a standardized hardness block of 380 g in mass for Shore hardness testing must be tested on an anvil of 8 kg in mass fixed to the testing machine frame: Meanwhile, the use of heavy hardness test blocks of around 2.7 kg in mass is prescribed for HLD and HLE Leeb hardness testing. However, it is our opinion that using an anvil fixed to the testing machine frame, as prescribed in the JIS for Shore hardness, could enable better control of Leeb hardness tests as well even if test blocks of a normal weight are used.

2.2. Errors in Velocity of Indenter Before and After Striking a Test Specimen

If rebound hardness is determined from the ratio of the indenter's velocity before and after it strikes the specimen, as is the case for Leeb hardness and small ball rebound hardness (HNM) tests, the fact that, if velocity V_1 before the impact changes, velocity V_2 after the impact changes accordingly should be a favorable factor from an industrial standpoint. In fact, in small ball rebound hardness tests (HNM) using three-millimeter alumina and cemented carbide indenters, changing the impact velocity V_1 by 20% would only cause a maximum change of around 4% in indenter velocity ratio, or coefficient of restitution "$e = V_2/V_1$," as shown in Fig. 9. Accordingly, the tolerance of 0.1% for errors in impact velocity V_1 specified by the proposed ISO standard for hardness test blocks could translate into a tolerance of 0.02% or less for hardness value errors based on the coefficient of restitution. This is an extremely severe tolerance level, compared to the tolerance of 4.88% (2.05 ± 0.1 m/s) for impact velocity V_1 specified by the ISO standard for hardness testing machines and to the accuracy of test force specified for the aforementioned indentation hardness tests[5] [6].

2.3. Formula for Converting from Vickers Hardness into Rebound Hardness

It is no exaggeration to say that the development of rebound hardness tests in Japan has been promoted by the Roll Hardness Committee of the Material Testing Research Association of Japan. Based on the study results of the Committee, the method of controlling rebound hardness values using the Vickers hardness—a highly reliable method of static indentation hardness testing—was first proposed in 1944 and developed exclusively in Japan. In 1965, this Vickers-to-Shore conversion method, or the VHS method, was included in the JIS test block standard for Shore hardness, and has since contributed to promoting the spread of Shore hardness testing in Japan, which is not, however, common internationally,. Twenty three years after it was established as a JIS, the VHS method has been improved to what it is now by revising the conversion formula based on careful reviews of the Vickers to Shore converted hardness values.

The Roll Hardness Committee also investigated the relation of conversion from Vickers to the Leeb hardness scales HLD and HLE, with the cooperation of manufacturers of hardness testers, and in 1990 developed a hardness test block made of eutectoid carbon steel to be used exclusively for Vickers to Leeb conversion purposes. This block, as with JIS Shore hardness test blocks, is only made of eutectoid carbon steel and is available in dimensions of 115 mm in diameter and 33 mm in thickness to ensure reliability of conversion, and has been successfully used for more than 25 years in Japan. In recent years, the conversion relationships between Vickers and HLD and HLE have been reviewed several times using the newest HLD and HLE testers each time. As a result, a revision of the conversion formulas is now proposed, as shown in Equations (1) and (2) and Fig. 10.

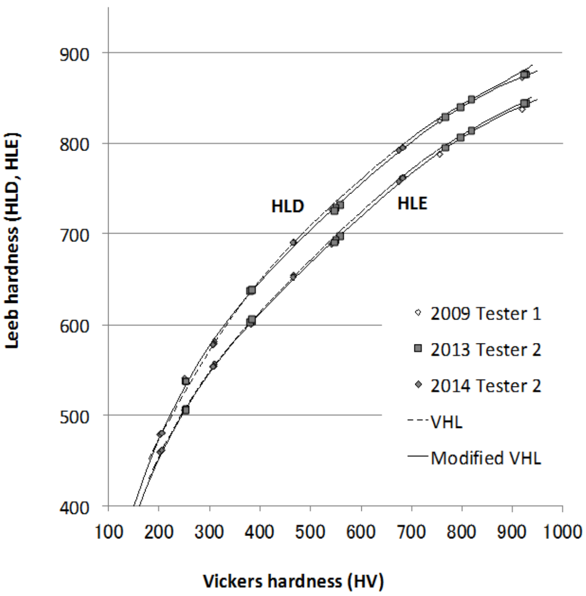

Fig. 10 Comparison of Vickers-to-Leep conversion formulas before and after their modification when tested with the HLD and HLE test blocks made of eutectoid carbon steel and designed by the Roll Hardness Committee

$$VHLE = 3.82045HV - 0.0107606HV^2 + 1.75250 \times 10^{-5}HV^3 - 1.40442 \times 10^{-8}HV^4 + 4.32223 \times 10^{-12}HV^5 \quad (1)$$

$$VHLD = 3.89473HV - 0.0103653HV^2 + 1.60318 \times 10^{-5}HV^3 - 1.23218 \times 10^{-8}HV^4 + 3.65212 \times 10^{-12}HV^5 \quad (2)$$

In this way, we believe it is practical and effective to use the highly reliable hardness values of static indentation tests to help increase the reliability of hardness values of dynamic hardness tests, such as rebound hardness[7] [8].

3. DISCUSSIONS

To summarize the discussion so far, let us provide our opinions on the following issues we believe to be very important.

(1) Whether it is included in the main text of standards or appendices, any statement concerning uncertainty should be provided only for reference purposes. For example, we oppose the revised ISO/FDIS 6508: 2014 Part 3 standard on reference blocks for Rockwell hardness tests in that paragraph 8.3 additionally requires the inclusion of an uncertainty statement in a document attached to the test block. Instead, we propose to delete the additional requirement and recover the original paragraph as one in the corresponding DIS standard.

(2) Regarding the loading time specified in the hardness test block standards, we would like to propose abolishing the misleading statement that presents the time that is not the median value of the allowable range of loading time as a standard time. Instead such range should be specified by simply setting the lower and upper ends. For example, paragraph 7.6 of the ISO/FDIS 6506:2014 Part 1 standard on the Brinell hardness test specifies a standard loading time of 7 seconds, and the tolerable range of loading time as +1 to -5 seconds. This expression may be the result of prioritizing the convenience of the creator of the standard, and is highly misleading. The statement should be made much simpler and just specify the tolerable range as 2 to 8 seconds.

(3) For the direct accuracy of test forces specified in the hardness test block standards, unnecessarily severe tolerance ranges tend to be specified irrespective of whether they actually produce justifiable effects. Specifically, the ISO/FDIS 6508: 2014 Part 3 standard for hardness test blocks specifies the error tolerance for the force applied after the total test force is removed as 0.2%, but this should be relaxed.

(4) Because the usefulness of a reference indentation for Brinell hardness tests is expected only for a comparison among operators or measuring devices, the power of a microscope should be calibrated with a highly reliable standard scale or equivalent, not by using an indentation, which is three dimensional and the image thereof is subject to the conditions under which it is observed. Accordingly, we propose to delete the additional provision in paragraph 4.4.3 of the ISO/FDIS 6506: 2014 Part 2 standard for hardness testing machines that requires agreement within 0.5% of the diameter of a reference indentation measured with an indentation diameter measuring device and the standard value, or the provision should be revised so that a reference indentation can only serve as a reference tool for the purpose of comparison. In this connection, we propose to abolish or provide only for reference purposes the provision concerning the number of test points in paragraph 6 of the Part 3 standard for hardness test blocks and the statement concerning a reference indentation in the provision for documents attached to a test block in paragraph 8.3 of the said standard.

(5) Regarding the ISO/DIS 16859 (2013) standard for Leeb hardness, there have not yet been sufficient discussions as a whole. As to the issue of traceability, in particular, there have not been sufficient historical results to establish an international consensus. We are concerned that hasty standardization may result in arbitrary statements. If the standardization of Leeb hardness has to be achieved at any cost as soon as possible, all those statements should be provided for reference. For example, the material of HLE indenters is only specified to be “polycrystalline diamond (PDC)” in Table 1 of the Part 1 standard. This will only limit the manufacture of HLE testers to certain players and could jeopardize the meaning of establishing an international standard. As another example, let us cite the provision of the Part 3 test block standard, specifying the error tolerance for an indenter ejection velocity of 2.05 m/s with a standard hardness tester as 0.0025 m/s, or 0.12%, which only makes us doubt whether the validity and viability of the standard has ever been confirmed. The ISO/DIS 16859 (2013) standard for Leeb hardness seems to have much room for further discussion.

4. RESEARCH AND REVISION AIMED AT ACHIEVING THE MOST REASONABLE HARDNESS TESTING METHODS THAT ARE EFFECTIVE IN ACTUAL INDUSTRIAL APPLICATIONS

In conclusion, let us put forward our position on ISO standards. First, we think the efforts for ISO standardization of hardness test methods should center on certain methods that are very important for industrial purposes. Test methods that require tremendous efforts for control and operation should be regarded as having much room to be developed or have not been sufficiently developed. Adding unnecessarily strict provisions to tightly standardize rather simple test methods would only enlarge the volume of standards meaninglessly, which could hinder the wider use of hardness tests and lose the confidence of users. Regarding the issue of hardness uncertainties, we are afraid that establishing seemingly plausible calculation formulas to seek strict tests, such as on material strength, with which it is physically or practically impossible to achieve perfect strictness, would only increase the cost of hardness testing unnecessarily and fan meaningless competition over uncertainty values that are far removed from reality. Even if making an uncertainty statement is considered reasonable, such a statement should be made by giving empirical and realistic uncertainty values, based on the actual results of comparative measurements or the equivalent. From these perspectives, we believe consistent efforts are required to simplify and streamline the ISO standards and that the discussions for that purpose should not only take place whenever new standards are established or existing ones are revised, but also be held in a continuous basis.

The aim of research and studies carried out by professionals such as ourselves on hardness tests should also be set for achieving the most reasonable hardness testing method that is effective in actual industrial applications. We believe that continuing steady efforts in such a direction will ensure the continued improvement of hardness standards.

Finally, we express our sincere gratitude to Dr. Satoshi Takagi and others who have participated in the ISO TC164 SC3 and worked continuously to enhance hardness standards.

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