Establishing a common Rockwell hardness scale using geometrically calibrated standard diamond indenters

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Establishing A Common Rockwell Hardness Scale Using Geometrically Calibrated Standard Diamond Indenters

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Abstract: Recently developed microform measurement techniques have reduced the measurement uncertainties in the geometry of Rockwell diamond indenters. In this paper, we describe several intercomparisons to determine if tightly controlled indenter geometry can improve the consistency of Rockwell C hardness (HRC) measurements. First, using a common indenter, five national laboratories obtained a total performance variation range of (-0.19 to +0.16) HRC on a set of hardness blocks with nominal hardness values ranging from 30 HRC to 60 HRC. Second, a set of 11 indenters with tightly controlled geometrical parameters produced a performance variation range of (-0.17 to +0.23) HRC from 25 HRC to 60 HRC when tested in a single deadweight hardness machine. The consistent geometries of these indenters were verified both with a stylus instrument and a laser interferometer. Third, a similar intercomparison of eight indenters provided by NIST and NRLM and calibrated by a stylus instrument yielded a variation range of ±0.19 HRC from 25 HRC to 60 HRC. These results support the feasibility of establishing a worldwide unified Rockwell C hardness scale using geometrically calibrated standard indenters with consistent geometry and hardness performance. It should be possible to establish a common Rockwell C hardness scale with an expanded uncertainty of approximately ±0.2 HRC and without significant bias with respect to an ideal scale.

Keywords: Rockwell hardness, HRC, diamond indenter.

1. Introduction

Rockwell Hardness (HR) is the most widely used mechanical testing method for metal products. However, the HR scales of different countries are not unified. This could result in technical barriers to trade. The development of ISO 9000 quality standards provides a strong motivation to establish worldwide unified Rockwell hardness scales.

Rockwell hardness scales are empirical, and as such are defined by reference standards (standard testing machines and indenters) and reference testing conditions. A Rockwell scale is established by the performance of a standard diamond indenter (for the HRC, HRD, HRA, HR45N, HR30N and HR15N scales) using a standard testing machine and a standardized testing cycle (include loading velocity and holding times). For many years, efforts in Rockwell hardness standardization have mainly concentrated on three aspects:

(A) To develop standard machines and direct verification techniques;
(B) To develop standard diamond indenters and microform calibration techniques;
(C) To control the testing cycle and to develop a standardized testing cycle.

Since the 1940's, standard hardness machines have been developed at different laboratories[1-4]. More recently deadweight and laser-type standard machines, developed at IMGC (Italy)[3], NIM (China)[4], MPA NRW (Germany) and NIST (U.S., a new version of IMGC machine), have shown measurement repeatability better than ± 0.1 HRC ($\pm 2\sigma$).

However, significant differences in Rockwell hardness tests came from the testing cycles and the indenters' geometry. There is a large variation of the testing cycles among national laboratories and between national laboratories and industries[5]. In order to establish a worldwide unified scale, it is necessary that the national laboratories use a common standardized testing cycle, including the loading velocity and holding times.

From the 1950's to the 1980's, different measurement techniques were developed for the geometric measurements of the diamond indenters[6-9]. However, the expanded measurement uncertainties for the 200 μm tip radii were reported to be in the range of micrometers[7-9], or sometimes even larger[8]. Many complex features of the diamond indenters, such as surface roughness and form errors, could not be explored and quantified. In addition, significant differences in geometry and hardness performance existed among different national indenters[10]. International comparisons of HRC tests using national indenters showed a variation range of ± 0.9 HRC[11]. The non-unified testing cycles along with the non-unified microform geometries of the national indenters are largely responsible for these differences. The former is mainly a standardization issue; the solution would be an international agreement on a standardized testing cycle for worldwide unified scales. The latter is a metrology issue; the solution is based on precision metrology to establish high quality standard Rockwell indenters[12].

In order to establish and to maintain a constant national Rockwell scale, a systematic correction method was proposed at NRLM for the hardness measurement results of some collective national indenters. This system has been used in Japan for the control of the uniformity of the national hardness scales since the 1960's[13]. // Hilo

Since the 1980's, HRC scales have been locally unified in European Community countries by averaging several national scales based on each country's national hardness machines and national indenters[14]. Although the unified scale is based on the mean of several national indenters, the unified scale has an unknown bias to an ideal scale and lacks metrological traceability and reproducibility.

In the U.S., private companies have maintained their own internal scales using "historical" hardness blocks [15], with unknown biases between these scales and an ideal scale. As these "historical" blocks were used up, they were replaced by new blocks, possibly compromising the consistency of these scales over time. To remedy this state of affairs, development of a standard testing machine for Rockwell hardness was undertaken and completed at NIST in the early 1990's, with ongoing development of standard Rockwell diamond indenters and metrological traceability.

Ideally, a worldwide unified Rockwell scale should be characterized by:

(A) Metrological traceability: The reference standards are established through fundamental measurements with tightly controlled tolerances and acceptably small measurement uncertainties. These include the force and displacement calibrations for the standard machines, and the microform calibrations for the standard indenters. The Rockwell scale established in accordance with these references standards has metrological traceability without significant bias to an ideal scale.

(B) Stability and reproducibility: Stability and reproducibility of the reference standards and Rockwell scales are ensured by fundamental measurements. Each standard (machine or indenter) can be replaced by other qualified standards. The reproduced reference standards can perform the same function as the original ones without causing the common scale to drift outside the certification range.

(C) Transparency and independency: The procedures, techniques and reference standards used for establishing the common scale should be well known and should be independently reproduced by another laboratory to create and maintain the same hardness scale without significant bias.

The worldwide unified scale could be achieved by establishing the reference standards (standard machines and standard indenters) through fundamental measurements, and standardizing the testing cycles. High accuracy standard machines were developed based on force and displacement calibrations[3,4]. Since the 1990's, stylus and laser interferometry techniques have been used for the microform measurements of diamond indenters. These techniques have largely reduced the measurement uncertainties. By using a laser interferometer with a tailored wavefront, an expanded measurement uncertainty of ± 1.5 μm for the tip radii and $\pm 1.1'$ ($\pm 0.018°$) for the cone angles were reported at MPA NRW[16]. By using a commercial stylus instrument, an expanded measurement uncertainty of ± 0.4 μm for the tip

The national indenters were chosen on the basis of geometrical measurement, and the machines are metrologically of the metrological type therefore the expected bias is limited.

radii and $\pm 0.01°$ for the cone angles were reported at NIST[17]. The complex geometric features of Rockwell diamond indenters, including the profile deviations from the least squares radii, the cone flank straightness, the holder axis alignment error, the surface roughness and surface defects, can also be explored and quantified[17].

It is now possible to establish a worldwide unified scale based on these newly developed measurement techniques, instead of on performance comparisons and corrections to offset the significant differences of diamond indenters. The key point is to prove that geometrically calibrated standard indenters could significantly improve the hardness measurement consistency to an acceptable amount, and that these standard indenters could be produced by different manufacturers and calibrated by different measurement techniques. In this paper, we introduce a joint study by five laboratories which are currently responsible for national Rockwell standards. We discuss the characteristics of the proposed standard indenters in Section 2. We compare the performance differences of five different national indenters with respect to a common indenter in Section 3. We compare the geometric measurements and hardness testing results for several indenters in Sections 4 and 5. With closely controlled geometries, the hardness tests for these indenters show a performance variation range of approximately ± 0.2 HRC. In Sections 6 and 7, we present some conclusions and a discussion on the standardized testing cycle.

A general conclusion is that the use of geometrically calibrated and performance verified standard indenters in different national standard machines with a standardized testing cycle should enable the establishment of a common HRC scale within an expanded uncertainty of approximately ± 0.2 HRC. This common scale could be independently established in different national laboratories with metrological traceability and reproducibility and without significant bias to the ideal scale.

2. Characteristics of working grade, calibration grade and the proposed standard grade Rockwell diamond indenters

2.1 Geometric and non-geometric properties of Rockwell diamond indenters

The Rockwell diamond indenter is a diamond cone with 120° cone angle blended in a tangential manner with a spherical tip of 200 μm radius. Both geometrical and non-geometrical properties affect the hardness performance of the indenters. We discuss these properties as follows[18].

2.1.1 Geometrical Properties The geometrical parameters of the Rockwell diamond indenters include:

(A) The parameters for the spherical tip surface, which include:
- the mean radius;

- the maximum and the minimum radius in different measurement sections;
- the form errors of the spherical tip, which can be characterized by the maximum profile peak and profile valley deviations from the least squares shape.

(B) The parameters for the cone surface, which include:
- the mean cone angle;
- the maximum and the minimum cone angle in different measurement sections;
- the form errors of the cone surface which can be characterized by the maximum cone flank straightness error.

(C) The holder axis alignment error.

(D) The surface roughness and surface defects.

2.1.2. Non-geometric Properties The non-geometrical properties of the Rockwell diamond indenters include:

(A) The mechanical properties of the diamonds, and
(B) The soldering of the diamond prism into the holder.

The crystallographic orientation of the diamond is not a direct cause of the performance differences of the diamond indenters[19]. However, the orientation of the crystallographic axes will affect some features of the geometric form, such as a three or four lobed shape and a certain degree of flatness or sharpness with respect to a spherical tip, which will affect the hardness performance of the indenters[19,18]. The effects of non-geometric properties can be considered lower than the effects of geometrical properties for working and calibration grade indenters

2.2 Working grade and calibration grade Rockwell diamond indenters

There are two grades of Rockwell indenters specified in ISO, ASTM and CEN standards[20-24]. The working grade indenters specified in ISO 716[20], ASTM E18-94[22] and EN 10109-2[23] are used for ordinary hardness tests. The calibration grade indenters specified in ISO 674[21], ASTM E18-94[22] and EN 10109-3[24] are used for calibration of the secondary Rockwell blocks. The geometric tolerances and hardness performance requirements for the two grades of diamond indenters are shown in Table 1.

2.3 Proposed standard grade Rockwell diamond indenters

Different national laboratories use different indenters, which are recognized as the reference standards at the national level[21,24] as clearly required by ISO 674 and EN 10109. However, there is no common international realization[25]. Geometric measurements and hardness tests have shown that the quality of currently used national indenters is no higher than a calibration grade level, which is specified for the calibrations of the secondary blocks. For the purpose of establishing a worldwide unified Rockwell scale with metrological traceability and reproducibility, it is necessary to

~~ISO 674 and EN 10109-3 specifications recognise the necessity of high reference indenters, defined as the indenters recognised as reference indenters at national level.~~

define a higher-quality standard for Rockwell indenters. The standard indenters should be characterized by high uniformity for their microform geometry and hardness performance, and would therefore, be interchangeable and reproducible[18]. Development of different microform measurement techniques[16,17] has made it possible to establish standard indenters in different national laboratories with tightly controlled tolerances and measurement uncertainties.

Technical requirements for geometric tolerances and performance uniformities of the standard indenters have been proposed by NIST[18], and are shown in Table 1. The geometric tolerances of the proposed standard indenters are designed for a performance uniformity range of ±0.15 HRC without significant bias to an ideal scale[18].

(Note: Although the ISO Guide to the Expression of Uncertainty in Measurement[25] recommends that measurement uncertainty be reported in terms of standard uncertainty (i.e., standard deviation) multiplied by a coverage factor of $k = 2$, the current hardness standards[20-24] and measurement practices still use the variation range. For a normal distribution, the mean of the range $a_{(Ra)}$ can be estimated from the standard deviation σ: $a_{(Ra)} = d_n \sigma$, where d_n is a coefficient depending on the sample size n, see Ref.[26].)

The geometric form errors of diamond indenters have significant effects on the hardness tests, especially for the small loading HR tests (HR45N, HR30N and HR15N), and should be well controlled. These form errors include the profile peak and profile valley deviations from the least squares radii and the cone flank straightness. In order to test the diamond indenters overall, four performance tests on 20 HRC, 55 HRD, 43 HR45N and 92 HR15N for the working and calibration grade indenters were included in EN 10109 standards[23,24]. The performance requirements for other HR scales of the NIST proposed standard indenters are still under investigation and will be specified later.

In addition to the geometric features of the diamond indenters, some non-geometric properties may affect hardness performances. It is possible that an individual geometrically qualified standard indenter may show significant difference of hardness performance from the others. For this reason, the geometrically qualified standard indenters still require hardness performance verification tests.

The performance uniformity of ±0.15 HRC discussed above is close to the combined random variation range of the standard machine and standard blocks[18]. Any performance tests of the diamond indenters includes the random variations of the standard machine, as well as the random non-uniformity of the standard blocks. For the standard machines, the random repeatability was reported as no more than ±0.1 HRC ($\pm 2\sigma$)[3,12]. For the standard blocks, the non-uniformity tested at NIST showed a total range of less than ±(0.1 to 0.2) HRC in seven indentations. Therefore, if geometrically qualified standard indenters show a performance variation range within ±0.15 HRC (including random variations of standard machine and standard blocks), it is reasonable to conclude that the hardness performances of these standard indenters would have been unified without significant systematic bias among them. The Rockwell scale established using these standard indenters in a standard machine with a standardized testing cycle would then have metrological traceability and reproducibility without significant bias to the ideal scale. Following this approach, the expanded uncertainty of the common Rockwell scale calculated by a quadratic sum of different uncertainty components, could be expected to be about ± 0.2 HRC.

3. Hardness comparison tests between a common indenter and five different national indenters

A key point is to show that geometrically calibrated and qualified standard indenters, which could be produced by different manufacturers and calibrated by different measurement techniques, can enable hardness measurement consistency to an acceptable amount. First, as a reference, we estimate the existing hardness variation range among five different national indenters with respect to a common indenter. Then, we compare the geometry measurements and hardness tests of 16 indenters made by different manufacturers. The geometric parameters of these indenters are measured by different techniques, and are close to meeting the technical requirements for the proposed standard indenters.

A common indenter and a single set of hardness blocks with nominal hardness values of 30, 40, 50 and 60 HRC were tested by five Rockwell hardness machines in different laboratories. A nominal testing cycle was specified having the following dwell times and indenter velocity (*the actual testing cycles and tolerances used by different laboratories are to be added later*):

- Preliminary force dwell time on loading = 8 s; , when attaining
- Indenter velocity ~~from 98 N (10 kgf) to~~ 1471 N (150 kgf) = 10 μm/s;
- Total force dwell time = 10 s;
- Preliminary force dwell time on unloading = 5 s.

At each laboratory, each block was first tested by four indentations using a common indenter. Fig. 1 shows deviations from the average hardness values. The zero line comes from the mean hardness values of the five national laboratories. In this paper, we report the total variation range of hardness tests in the whole testing range, rather than the ranges at different hardness testing levels. The testing results show good agreement with a total range of (-0.19 to +0.16) HRC. This is because the national hardness machines were directly verified by fundamental measurements of the force and displacement, and all national laboratories used a common testing cycle for this study. The small variations shown in Fig.1 mainly represent the small differences among five national standard machines and testing cycles, as well as the possible non-uniformity of the standard blocks.

The hardness tests were repeated using the laboratory's own indenter. The variation range increased to (-0.29 to +0.38) HRC (see Fig. 2), which represents the combined variation range of five different national indenters, national machines and testing cycles. If we subtract the testing results using a common indenter (see Fig. 1) from those using different national indenters (see Fig. 2), the variation range is (-0.33 to +0.44) HRC (not shown), which mainly represents the existing performance differences of the five national indenters augmented somewhat by the random errors arising from the subtraction of two sets of measurements.

4. Comparisons of geometric measurements and hardness performance tests

Nine Rockwell diamond indenters made by diamond manufacturer A were measured both by a stylus instrument at NIST[17], and by a laser interferometer at MPA NRW[16]. The geometric measurement results for the mean tip radii and the mean cone angles are compared in Table 2 for the two instruments. NIST's expanded uncertainty is a combination of non-uniformity of the measured indenter and the expanded measurement uncertainty, which is ± 0.4 μm for the tip radius and $\pm 0.01°$ for the cone angle[27]. The NIST expanded uncertainty represents a 95% confidence interval. For the MPA NRW results, the combined expanded uncertainties reported are ± 2 μm for the mean radii and $\pm 4'$ ($\pm 0.067°$) for the mean cone angles, which include the expanded measurement uncertainties of ± 1.5 μm and $\pm 1.1'$ ($\pm 0.018°$, both are with a coverage factor of $k = 2$) respectively[16].

Based on the expanded uncertainties reported by the two laboratories, U_a and U_b, we can determine whether or not there are significant differences between the two sets of measurements. If the measurement difference for the mean radius or mean cone angle is $\delta =$ (a) - (b) (see Table 2), and if $\delta > U = (U_a^2 + U_b^2)^{1/2}$, we can conclude that there is a significant difference between these two measurements[12].

From Table 2, we can see that all nine indenters show good agreement between the two measurement techniques for the mean cone angle measurements $(\delta << U)$. For the mean tip radii measurements, seven indenters show acceptable agreement $(\delta < U)$. Compared with a 17 μm range for a single indenter's mean tip radius measured at four laboratories and reported in 1987[10], the measurement agreement of the mean tip radii have been significantly improved by using stylus and laser interferometry techniques. However, two indenters (No. 3307 and No. 3312) show significant measurement differences between the two techniques $(\delta > U)$. The mean radii of these two indenters measured by the laser interferometer are significantly larger than those measured by the stylus instrument. It is believed that the difference of the window sizes used by the different instruments is one of the causal factors. For the stylus instrument, a (-100 to +100) μm window is used for the least squares radii and profile deviation evaluations, and a (-450 to -100) μm and a (+100 to +450) μm window are used for the cone angles and cone flank straightness evaluations. For the laser interferometer, the window is a circular area with radius of 91 μm for the tip radius evaluations and an annulus with inner radius of 110 μm and outer radius of 500 μm for the cone angle evaluations. If the measured indenter had a perfect geometric form, there would be no measurement differences using the different window sizes by the two measurement techniques. However, because of the geometric form errors, especially in the transition area from the cone surface to the spherical tip of the measured indenter, different window sizes result in measurement differences. The amount of the differences depends on the type and amount of the form errors, as well as the window sizes used. In order to compare the geometric measurements of diamond indenters using different measurement techniques, the window sizes will have to be unified.

Two other indenters measured at NIST previously[18] were added to the set of nine. One of them was made by a different manufacturer B from the other ten indenters made by manufacturer A. The total of 11 indenters showed a range of mean radii from 198.34 μm to 202.90 μm, and a range of mean cone angles from 119.94° to 120.07°, according to the measurement results with the stylus instrument. These indenters nearly meet the technical requirements for the proposed standard indenters. However, the profile deviations from the least squares radius and the cone flank straightnesses must be improved[18].

All 11 indenters were tested by the NIST standard deadweight machine using the same testing cycle. Four HRC hardness blocks with nominal hardness values of 25, 35, 50 and 60 HRC were used for the tests. For each hardness test, four indentations were made on the same block. The deviations from the average hardness values are shown in Fig. 3. The zero line comes from the average values of the 11 indenters. The total performance variation range is (-0.17 to +0.23) HRC from (25 to 60) HRC for all 11 indenters, including the variation of the testing machine and the non-uniformity of the hardness blocks. These results strongly suggest that the improved standard indenters could produce a hardness measurement uniformity of ±0.15 HRC.

5. Comparisons of Rockwell diamond indenters made by different diamond manufacturers

Four of the previous indenters made by manufacturer A were then compared with five NRLM indenters made by manufacturer B, which were also measured by the stylus instrument at NIST. Table 3 shows the detailed geometric measurement results for each indenter. These results include the mean tip radii with expanded uncertainties, the maximum and minimum radii, the maximum profile peak and profile valley deviations, the mean cone angles with expanded uncertainties, the maximum and the minimum cone angles, the maximum cone flank straightness, the holder axis alignment errors with expanded uncertainties, and the mean and the maximum surface roughness Ra.

For the nine indenters, the mean tip radii range from 197.25 μm to 202.43 μm, which is close to the range of the 11 indenters previously discussed. The mean cone angles of the nine indenters range from 119.89° to 120.21°, which is larger than the range of the previous 11 indenters. The maximum profile peak deviations of the nine indenters range from 0.22 μm to 0.92 μm, and the maximum profile valley deviations range from 0.25 μm to 0.51 μm. The maximum cone straightness ranges from 0.15 μm to 0.49 μm. Differences in spherical tip shape were also observed between these indenters. In general, indenters made by one manufacturer showed flat-shape tips with respect to a spherical shape, while indenters made by the other manufacturer showed sharp-shape tips. These different shapes may affect the performance of Rockwell indenters, especially for the small loading HR tests (HR45N, HR30N, HR15N).

From Table 3, it can be seen that No.13392 indenter has the minimum mean tip radius (197.25 μm) and the maximum peak and valley deviations (0.92 μm and 0.51 μm) among all the nine indenters. Furthermore, its profile peak deviations measured in different measurement sections range from 0.55 μm (minimum) to 0.92 μm (maximum), which showed significant differences with respect to the other eight indenters.

The hardness performance tests for all nine indenters (see Fig. 4) show a total range of (-0.23 to +0.32) HRC for hardness between (25 to 63) HRC. However, the No.13392 indenter with the significant profile deviations shows performance bias with respect to the other eight indenters. When the data for this indenter are removed, the other eight indenters have a performance variation range of $\pm$ 0.19 HRC from (25 to 63) HRC (not shown). These results strongly suggest that standard indenters could be produced by different manufacturers with sufficient consistency both in geometry parameters and hardness performance.

Diamond manufacturers are currently working to fabricate the proposed standard grade Rockwell indenters. With the development of precision measurement techniques for measuring the indenters[16,17], the major quality issue is control of the correct shape. To date some indenters measured at NIST are close to meeting the technical requirements[18]. At least two diamond manufacturers believe that they can improve the manufacturing process and produce qualified standard indenters in the near future.

6. Summary

(A) A worldwide unified Rockwell scale should be characterized by metrological traceability, stability and reproducibility. It could be achieved by establishing the reference standards (standard machines and standard indenters) through fundamental measurements and by unifying the reference testing conditions. The standard machines and standard indenters could be independently established in different national laboratories. Different direct verification techniques with tightly-controlled tolerances and measurement uncertainties could be used to ensure the metrological traceability and reproducibility for these reference standards.

(B) Standard Rockwell diamond indenters would be characterized by high uniformity for both the microform geometry and hardness performance, and would therefore, be interchangeable and reproducible. Standard indenters could be produced by different manufacturers and calibrated by different measurement techniques. Stylus and laser interferometry techniques have shown significantly improved measurement agreements over previous techniques. In order to achieve a higher measurement agreement, the window sizes of the two approaches need to be unified.

(C) Geometric measurements and hardness tests among five laboratories show that a common indenter used in five national standard machines yielded a hardness variation range of (-0.19 to +0.16) HRC. Five existing different national indenters exhibited a hardness performance variation range of (-0.33 to +0.44) HRC. A set of 11 indenters was measured by a stylus instrument; nine of them were also measured by a laser interferometer. These indenters show consistent geometry and are close to meeting the technical requirements of the proposed standard indenters. The hardness tests for the 11 indenters show a variation range of (-0.17 to +0.23) HRC. Nine indenters made by two manufacturers measured by a stylus instrument also show consistent geometry. Their hardness variation range is (-0.23 to +0.32) HRC. However, when an indenter with significant profile deviation differences from the others is removed, the remaining eight indenters show a variation range of ±0.19 HRC. These results suggest that the proposed standard indenters could possibly obtain a performance uniformity range of approximately ±0.15 HRC.

(D) By using the geometrically calibrated and performance verified standard indenters in different national standard machines with a standardized testing cycle, it should be possible to establish a common HRC scale with an expanded uncertainty of approximately ±0.2 HRC. Unlike the scale established by performance comparisons and corrections within a local comparison loop, this common scale would have metrological traceability and reproducibility without significant bias with respect to the ideal scale. The proposed approach can also be used for unifying other HR scales using conical diamond indenters (HRD, HRA, HR45N, HR30N, and HR15N).

7. Concluding observation concerning the testing cycle

In addition to standard hardness machines and controlled indenter geometry, a unified Rockwell hardness scale requires a standardized testing cycle because of the sensitivity of HR readings to the dwell times (due to material creep) and to the strain rate[28]. This requires defining the characteristic parameters of the testing cycle and specifying their nominal values and tolerances. However, present U.S. and international standards specify a wide range for both the parameter values and tolerance requirements of the dwell times and indenter velocities[20-22]. In the EN 10109 standards[23-24], the indenter velocity is not specified. In general, therefore, the testing cycle is not completely defined, and those parameters that are defined have wide tolerances. Barbato et al.[28] have concluded that this situation can lead to hardness measurement differences larger than ±1 HRC.

There are different points of view on the testing cycle specification as reported by Petic and Barbato[5,28]. Industry tends to use a short testing cycle for efficiency and economy; national laboratories tend to use a long testing cycle to promote measurement reproducibility. The differences in testing cycles result not only in variations of hardness measurements, but also systematic shifts between different testing cycles[5,28].

It is therefore important to consider hardness metrology in the same way as other fields of metrology[5,28,12]. That includes developing an uncertainty budget by which all the influence quantities[12] are controlled to achieve a designed uncertainty for the hardness tests. According to Barbato et al.[28], the standardized testing cycle must be defined in such a way to get an acceptable uncertainty of the definition itself of the hardness scales.

In a recent proposal to establish a worldwide common scale for Rockwell hardness tests using diamond indenters[29], the expanded uncertainty was proposed as ± 0.2 HR unit. This uncertainty is a combination of the systematic and random errors from the machines, indenters, testing cycles and testing blocks. In this paper, we have shown that it should be possible to produce standard indenters with a performance variation range of ± 0.15 HRC with respect to an ideal scale, including the random errors of the machines and blocks. Therefore, the establishment of a worldwide common HRC scale with a ± 0.2 HRC expanded uncertainty will require a tightly controlled standardized testing cycle yielding a hardness measurement reproducibility range of no more than ± 0.15 HRC when using a common indenter in different national hardness machines.

The common indenter comparison discussed in Section 3 has produced a measurement reproducibility range of (-0.19 to +0.16) HRC in five national hardness machines (See Fig. 1), which is close to the proposed variation range mentioned above. It is not an implication that the testing cycle described in Section 3 is the best choice for a standardized testing cycle. However, it suggests that a tightly-specified test cycle is a practical, necessary step to achieving a higher level of consistency among worldwide Rockwell hardness measurements.

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25. *ISO Guide to the Expression of Uncertainties in Measurement,* ISO, Geneva, 1993, 88.
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27. Song, J.F.; Rudder, F.F. Jr.; Vorburger, T.V.; Smith, J.H., "Microform Calibration Uncertainties of Rockwell Diamond Indenters," *J. Res. NIST*, **100**(5), 1995, 543-561.
28. Barbato, G.; Desogus, S.; Germak, A., "Hardness Measurement from Empiricism to Metrology - An application to Rockwell C Scale," *Basic Metrology and Applications,* Libreria Editrice Universitaria Levrotto & Bella, Torino, Italy, 1994, 112-117.
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Captions of Figures and Tables:

Fig.1: A common indenter was tested by five national machines using a common testing cycle, the variation range is (-0.19 to +0.16) HRC.

Fig.2: Five national indenters were tested by five national machines using a common testing cycle, the variation range is (-0.29 to +0.38) HRC.

Fig.3: Performance comparisons of 11 indenters, the variation range is (-0.17 to +0.23) HRC.

Fig.4: Performance comparisons of nine indenters made by two manufacturers, the variation range is (-0.23 to +0.32) HRC.

Table 1. Technical requirements for three grades of Rockwell indenters and NIST expanded measurement uncertainties.

Table 2. Measurements comparisons using a stylus instrument at NIST and a laser interferometer at MPA NRW.

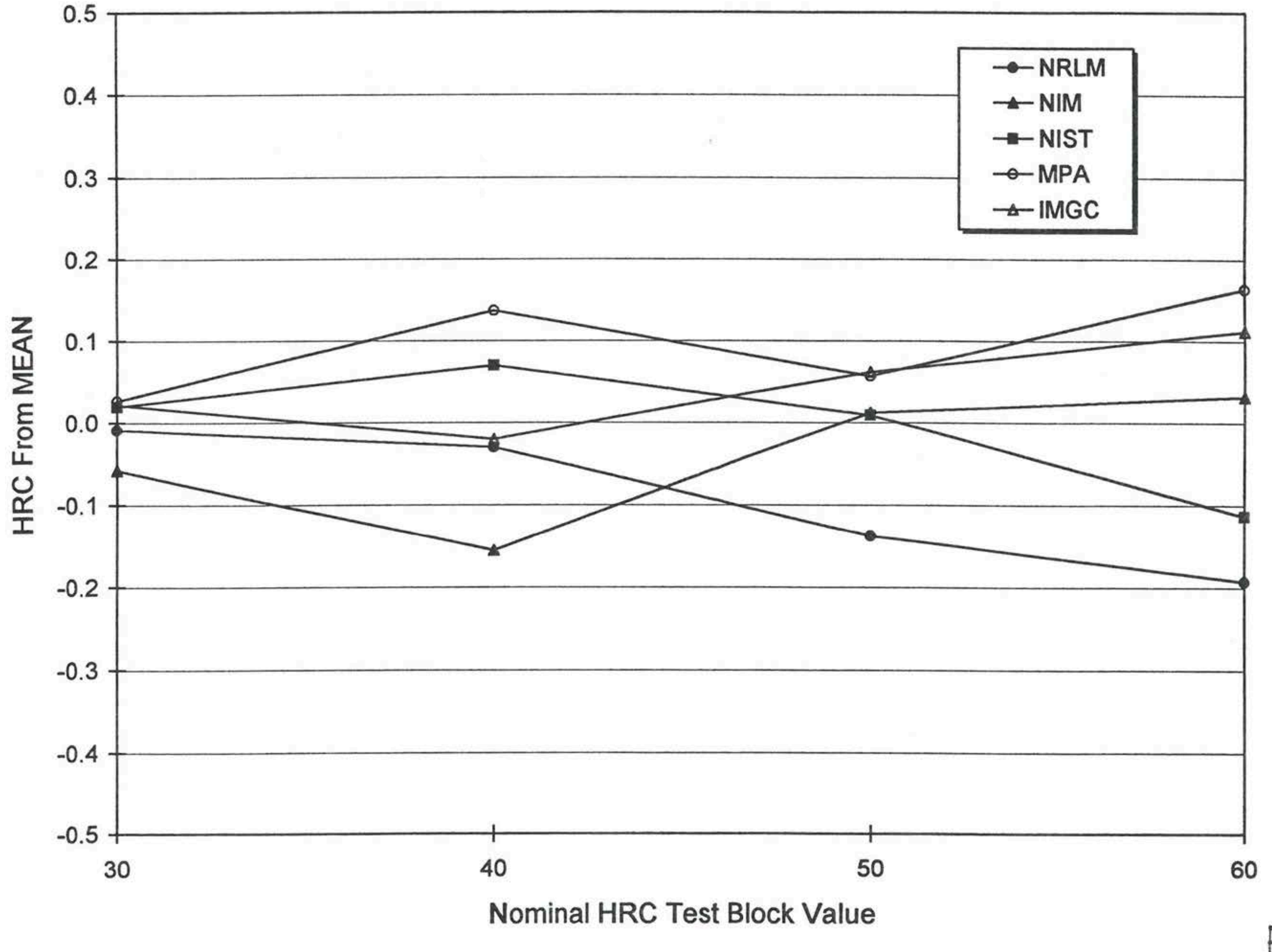
Table 3. Geometric measurement results of nine indenters from NIST and NRLM using a stylus instrument.

NEED TO DO:

Ask IMGC, MPA, NIM, and NRLM about the actual testing cycle used in Section 3.

(Mr. Yang: Please send me a copy of Ref[4] for your Laser Deadweight machine, I need information concerning the year and journal of this publication, as well as the testing data.)

- *06/13/1996, Draft for comments;*
- *07/09/1996, Draft for comments, 2nd Version, after T. Vorburger's comments;*
- *07/17/1996, Draft for comments, 3rd Version, after T. Vorburger's 2nd version comments;*
- *07/22/1996, Draft for comments, 4th Version, after S. Low's comments;*
- *07/23/1996, Draft for comments, 4-a and 4-b version, after T. Vorburger's comments;*
- *08/06/1996, Draft for comments, 5th Version, after Division and WERB reviewers' comments.*
- *09/09/1996, Draft for comments, 6th Version, after W. Liggett and K. Yee's comments and T. Vorburger's re-writing of the abstract and comments.*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NIM
NIST
MPA
IMGC
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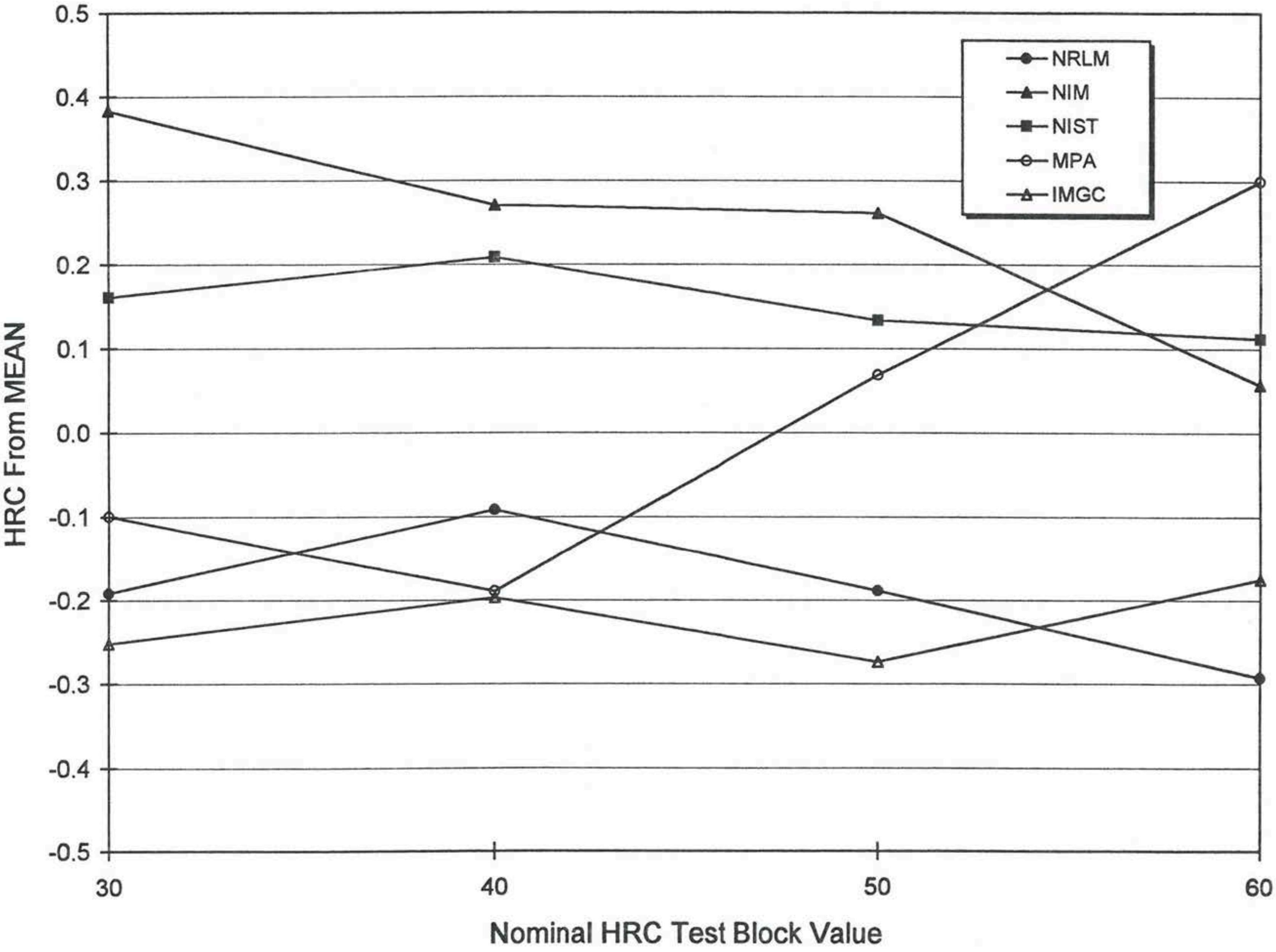
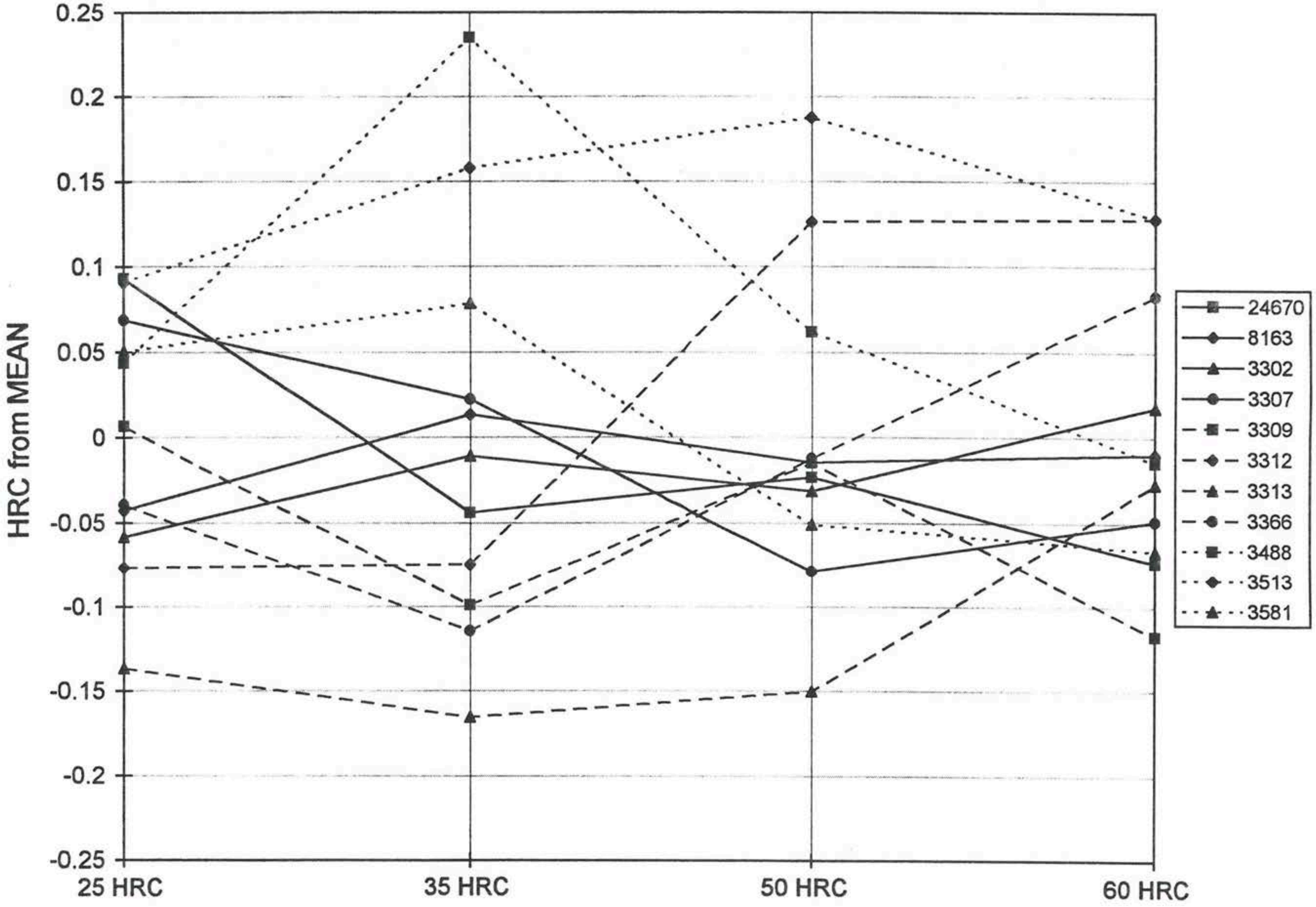
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
HRC From MEAN
30
40
50
60
Nominal HRC Test Block Value

Fig. 1



NRLM
NIM
NIST
MPA
IMGC
0.5
0.4
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
-0.4
-0.5
HRC From MEAN
30
40
50
60
Nominal HRC Test Block Value

Fig. 2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0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.25
HRC from MEAN
25 HRC
35 HRC
50 HRC
60 HRC
24670
8163
3302
3307
3309
3312
3313
3366
3488
3513
3581

Fig. 3

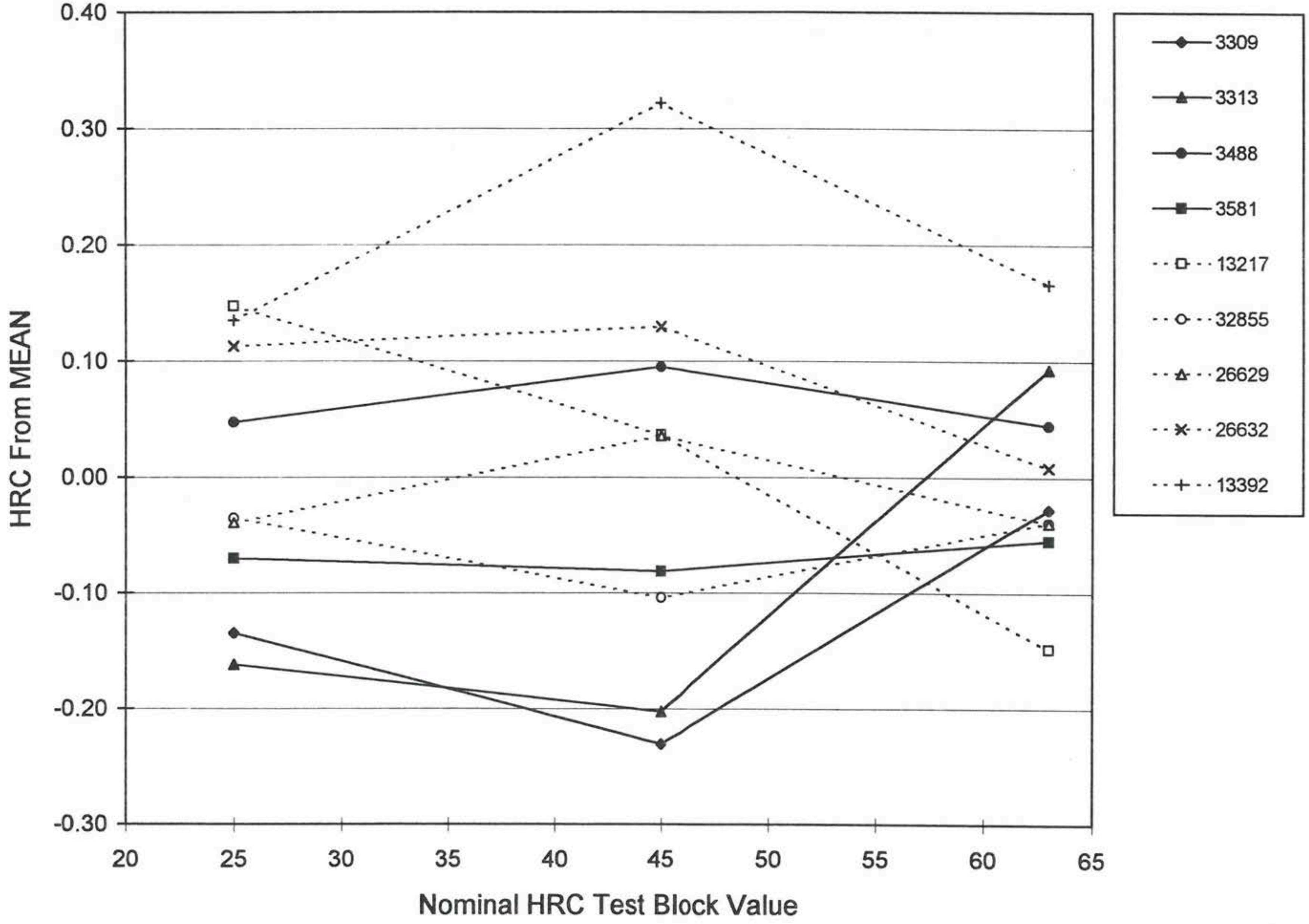
0.40
0.30
0.20
0.10
0.00
-0.10
-0.20
-0.30
HRC From MEAN
20
25
30
35
40
45
50
55
60
65
Nominal HRC Test Block Value
3309
3313
3488
3581
13217
32855
26629
26632
13392

Fig. 4

Table 1: Technical Requirements for Three Grades of Rockwell Indenters and NIST Expanded Measurement Uncertainties

Microform Geometry and Performance Uniformity Requirements	Tolerance			NIST Expanded Measurement Uncertainty (95%)
	Working Grade (ISO/716-1986, ASTM E18-94, EN 10109-2:1994)	Calibration Grade (ISO/674-1988, ASTM E18-94, EN 10109-3:1994)	Standard Grade (proposed by NIST)	
1. Spherical Radius				
1a. Least Squares Mean	200 ± 10 µm	200 ± 5 µm	200 ± 2.5 µm	± 0.4 µm
1b. Maximum Variation	200 ± 15 µm	200 ± 7 µm	200 ± 3.5 µm	
1c. Profile Deviation	± 2 µm$^{(1,2)}$, 4 µm$^{(3)}$	± 2 µm$^{(1,2)}$, 2 µm$^{(3)}$	± 0.25 µm	
2. Cone Angle				
2a. Least Squares Mean	---	120° ± 0.1°	120° ± 0.05°	± 0.01°
2b. Maximum Variation	120° ± 0.35°	120° ± 0.17°$^{(1,3)}$	120° ± 0.08°	
2c. Cone Flank Straightness	< 1 µm$^{(1,3)}$	< 0.5 µm$^{(1,3)}$	< 0.25 µm	
3. Holder Axis Alignment	± 0.5°	± 0.3°	± 0.15°	± 0.025°
4. Surface Finish				
4a. Surface Roughness Mean	---	---	R_a < 0.004 µm	
4b. Max. Surface Roughness	---	---	$R_a max$ < 0.005 µm	
Performance Uniformity Requirements	± 0.8 HRC$^{(1)}$ ± 0.8 HR$^{(3)}$ with respect to a standard indenter	± 0.4 HRC$^{(1)}$ ±0.4 HR$^{(3)}$ with respect to a standard indenter	± 0.15 HRC within a group of geometrically qualified standard indenters	

(1) Specified in ISO Standard; (2) Specified in ASTM Standard; (3) Specified in EN Standard, the performance uniformity is tested at 20 HRC, 55 HRD, 43 HR45N, and 92 HR15N.

Table 2. Measurement comparisons using a stylus instrument at NIST and a laser interferometer at MPA NRW

Indenter No.	Components		(a) Stylus Instrument	(b) Laser Interferometer	δ = (a) - (b) U = (Comb. Unc'ty)		Significant difference?
3309	Tip Radius	Mean	198.34 µm	198.39 µm	-0.05 µm	(δ)	
		Unc'ty (±)	2.04 µm	2 µm	2.86 µm	(U)	
	Cone Angle	Mean	119.98 °	120.00 °	-0.02 °	(δ)	
		Unc'ty (±)	0.03 °	0.067 °	0.07 °	(U)	
3581	Tip Radius	Mean	199.06 µm	198.64 µm	0.42 µm	(δ)	
		Unc'ty (±)	1.97 µm	2 µm	2.81 µm	(U)	
	Cone Angle	Mean	120.00 °	120.01 °	-0.01 °	(δ)	
		Unc'ty (±)	0.02 °	0.067 °	0.07 °	(U)	
3513	Tip Radius	Mean	199.17 µm	199.22 µm	-0.05 µm	(δ)	
		Unc'ty (±)	1.54 µm	2 µm	2.52 µm	(U)	
	Cone Angle	Mean	120.01 °	119.99 °	0.02 °	(δ)	
		Unc'ty (±)	0.03 °	0.067 °	0.07 °	(U)	
3302	Tip Radius	Mean	200.39 µm	200.20 µm	0.19 µm	(δ)	
		Unc'ty (±)	2.49 µm	2 µm	3.19 µm	(U)	
	Cone Angle	Mean	119.94 °	119.93 °	0.01 °	(δ)	
		Unc'ty (±)	0.07 °	0.067 °	0.10 °	(U)	
3488	Tip Radius	Mean	200.55 µm	201.13 µm	-0.58 µm	(δ)	
		Unc'ty (±)	0.75 µm	2 µm	2.14 µm	(U)	
	Cone Angle	Mean	120.07 °	120.06 °	0.01 °	(δ)	
		Unc'ty (±)	0.02 °	0.067 °	0.07 °	(U)	
3313	Tip Radius	Mean	200.82 µm	201.68 µm	-0.86 µm	(δ)	
		Unc'ty (±)	2.22 µm	2 µm	2.99 µm	(U)	
	Cone Angle	Mean	120.07 °	120.07 °	0.00 °	(δ)	
		Unc'ty (±)	0.06 °	0.067 °	0.09 °	(U)	
3366	Least Sq. Radius	Mean	202.02 µm	204.88 µm	-2.86 µm	(δ)	
		Unc'ty (±)	2.80 µm	2 µm	3.44 µm	(U)	
	Cone Angle	Mean	120.01 °	119.99 °	0.02 °	(δ)	
		Unc'ty (±)	0.05 °	0.067 °	0.08 °	(U)	
3307	Tip Radius	Mean	202.65 µm	207.56 µm	-4.91 µm	(δ)	***Yes***
		Unc'ty (±)	1.14 µm	2 µm	2.30 µm	(U)	
	Cone Angle	Mean	119.97 °	119.97 °	0.00 °	(δ)	
		Unc'ty (±)	0.05 °	0.067 °	0.08 °	(U)	
3312	Tip Radius	Mean	202.90 µm	206.77 µm	-3.87 µm	(δ)	***Yes***
		Unc'ty (±)	1.59 µm	2 µm	2.56 µm	(U)	
	Cone Angle	Mean	119.98 °	119.96 °	0.02 °	(δ)	
		Unc'ty (±)	0.05 °	0.067 °	0.08 °	(U)	

Table 3. Geometrical measurement results of nine Rockwell diamond indenters from NIST and NRLM by stylus instrument

Indenter No.	Spherical tip			Cone surface			Holder axis	Surface
	Least squares radii		Prof. dev.	Cone angle		Cone flank	alignment	roughness
	Mean *(Unc'ty)* (μm)	Max. Min. (μm)	Max. peak Max. val'y (μm)	Mean *(Unc'ty)* (°)	Max. Min. (°)	stra'tness Max. (μm)	error and *unc'ty* (°)	Ra mean Ra max. (μm)
NIST 3309	198.34 *(±2.04)*	199.66 196.30	0.43 0.46	119.98 *(±0.03)*	120.00 119.96	0.49	0.03 *(±0.03)*	0.0035 0.0038
NIST 3581	199.06 *(±1.97)*	200.69 197.63	0.40 0.29	120.00 *(±0.02)*	120.01 119.98	0.42	0.08 *(±0.02)*	0.0043 0.0045
NIST 3488	200.55 *(±0.75)*	201.05 199.92	0.34 0.25	120.07 *(±0.02)*	120.08 120.06	0.44	0.03 *(±0.02)*	0.0063 0.0097
NIST 3313	200.82 *(±2.22)*	202.28 198.74	0.51 0.46	120.07 *(±0.06)*	120.10 120.01	0.40	0.04 *(±0.03)*	0.0053 0.0077
NRLM 13392	197.25 *(±1.56)*	198.45 196.05	***0.92*** 0.51	120.03 *(±0.03)*	120.04 120.00	0.34	0.08 *(±0.03)*	0.0049 0.0055
NRLM 22629	199.07 *(±1.42)*	200.14 198.16	0.27 0.35	120.01 *(±0.02)*	120.02 119.99	0.37	0.12 *(±0.02)*	0.0035 0.0036
NRLM 13217	200.38 *(±2.40)*	202.75 198.72	0.24 0.37	120.11 *(±0.03)*	120.14 120.08	0.15	0.06 *(±0.02)*	0.0043 0.0047
NRLM 26632	201.34 *(±3.26)*	203.91 199.25	0.22 0.38	120.21 *(±0.03)*	120.24 120.19	0.17	0.03 *(±0.02)*	0.0036 0.0038
NRLM 32855	202.43 *(±2.63)*	204.33 201.71	0.26 0.46	119.89 *(±0.06)*	119.94 119.84	0.21	0.08 *(±0.03)*	0.0036 0.0038