Worldwide Comparisons of Rockwell Hardness Scales That Use a Diamond Indenter

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1. Abstract

The United States has participated in two major worldwide comparisons of Rockwell hardness scales over the past twenty years. In 1983, fourteen countries participated in a comparison of the Rockwell C scale. The latest worldwide comparison was completed in 1999, covering all Rockwell hardness scales that use a diamond indenter. Although the 1999 comparison showed improved agreement between the world's national hardness standardizing laboratories as compared to the 1983 study, there continues to be significant differences. This has led the Working Group on Hardness (WGH) of the International Bureau of Weights and Measures (Bureau International des Poids et Mesures, BIPM) to work towards reducing these differences by better defining Rockwell hardness test parameters and by initiating a new key-comparison of the capabilities of National Metrology Institutes to measure geometrical parameters of Rockwell diamond indenters.

2. Introduction

The Rockwell hardness test was developed by Stanley P. Rockwell [1] in 1919. He developed his test method as an improvement over other commonly used hardness tests of the time, which were hampered by long test times and sensitivity to surface preparation. Rockwell hardness is not a fundamental physical property of a material, as is, for example, mass and length. Like other mechanical properties of materials such as tensile or impact strength, Rockwell hardness is a property determined by an empirical test method. The American Society for Testing and Materials (ASTM) [2] defines 54 different Rockwell scales differing only in the type of indenter and force levels that are used. Six of the Rockwell scales use a diamond indenter. Because the hardness value is dependent on the definition of the test method, there are no alternative measurement systems to directly or independently measure Rockwell hardness, nor are there intrinsic artifacts to reference. Throughout most of the long and widespread use of the Rockwell hardness test in the United States, Rockwell hardness testing machines have been calibrated using commercially manufactured and calibrated test block standards. Prior to 1998, the certified values of the test blocks were, in most cases, traceable to either the calibration agency's own internally maintained standards, or to another commercial block calibration agency. Since 1998, the National Institute of Standards and Technology (NIST) has been producing test block transfer standards for some Rockwell hardness scales providing industry with traceability to the U.S. national Rockwell hardness scales [3,4].

The following is a brief account of the United States participation in worldwide intercomparisons of Rockwell hardness scales that use a diamond indenter. The results of these intercomparisons have influenced the measurement of Rockwell hardness in the United States, and have had a large effect on the world harmonization of Rockwell hardness scales.

3. U.S. Participation in OIML Comparison – 1983

In what was hoped to be a first step to achieve unification of hardness scales worldwide, a study [5] was conducted in 1983 under the framework of the member states of the International Organization of Legal Metrology (Organisation Internationale de Métrologie Légale, OIML) to investigate the differences between world hardness scales. The United States was one of 14 countries to participate in the study, which involved intercomparisons of the Rockwell C scale (HRC) and Vickers hardness (HV 30). The comparison procedure required that each country submit hardness reference blocks to a single laboratory for comparison (Československý Metrologický Ústav, Prague, Czechoslovakia). For this intercomparison, NIST (known in 1983 as the National Bureau of Standards) was, and continues to be, the metrology institute that represents the United States at OIML. At that time, NIST did not standardize the hardness scales to be investigated. To allow U.S. participation, NIST chose to submit commercial reference blocks from the Page-Wilson Corporation[1], which were considered by many to be the de facto U.S. hardness standards at that time.

The results of the OIML intercomparison study for the Rockwell C hardness scale are given in Figure 1. The data indicates that although there were variations between the HRC hardness scales of the participating countries, the upper range of the HRC scale (above 55 HRC) for the U.S. varied significantly from the majority of the other countries. A similar difference was reported in 1988 by Baker, Yamamoto and Yamamoto [6] in a comparison of commercial HRC reference standards of the U.S. and Japan.

4. NIST Rockwell Hardness Standardization

By the mid 1980s, there were increasing concerns by Rockwell hardness users in the United States that not only was the U.S. HRC scale different than the HRC scale of other countries in Europe and Asia, but also that the certified values of test blocks sold by different hardness calibration agencies in the U.S. did not always agree [7]. In 1991, at the urging of the ASTM and U.S. industry, NIST began the development of a national Rockwell hardness standardization facility. The goals of this program are to standardize the Rockwell hardness scales for the U.S.,

[1] Commercial equipment and materials are identified in order to adequately describe historical events. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

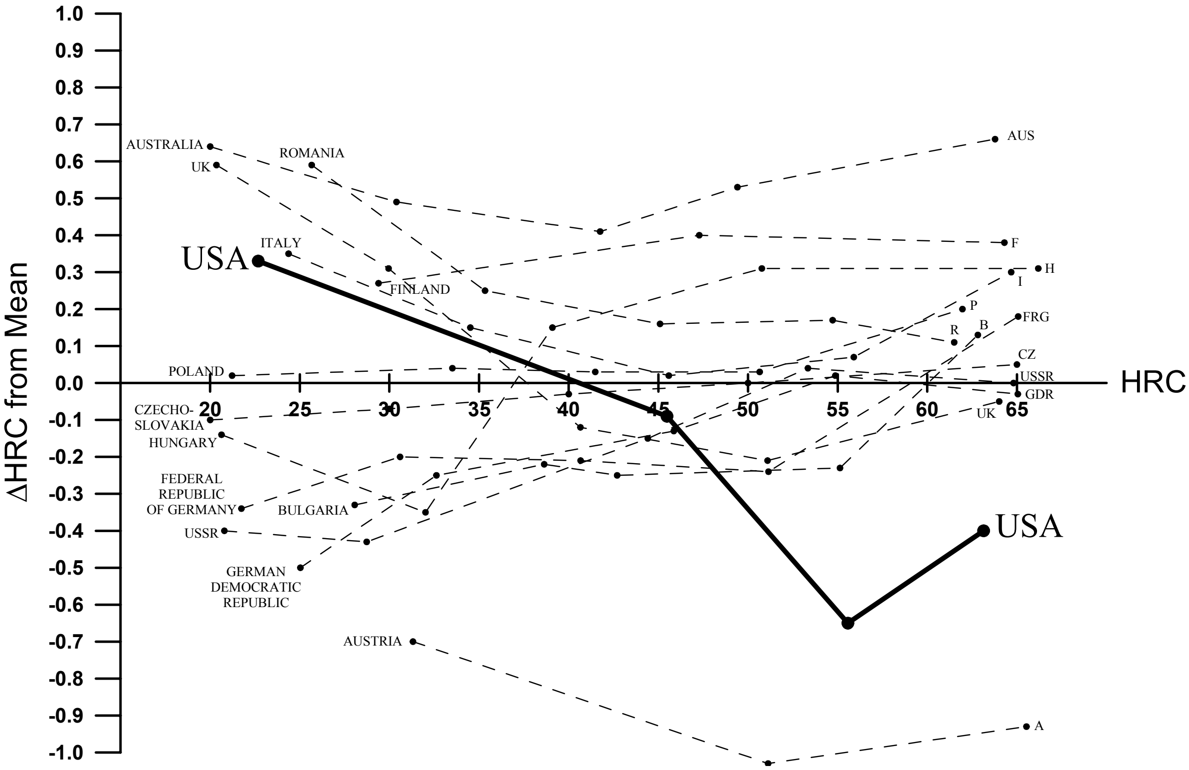

Figure 1. 1983 OIML intercomparison of the HRC scale.

and to provide industry with stable national transfer standards in the form of reference test blocks. In standardizing the Rockwell scales, NIST has employed instruments and procedures having the highest metrological accuracy as practicable.

In June 1998, NIST released the first Rockwell hardness reference test block standards for sale to industry. These blocks are for the HRC scale at three hardness levels, nominally 25 HRC, 45 HRC, and 63 HRC [8]. A significant result of the NIST standardization was that the hardness levels of the NIST scale deviated from the HRC scale used by U.S. industry at that time. The magnitude of the deviation varied by hardness level and depended on which calibration agency's reference test blocks had been used previously. Figure 2 demonstrates the general trend of the difference between NIST and U.S. industry HRC scales [9]. This trend should not be considered as an absolute offset; the relationship could possibly differ by as much as ±0.5 Rockwell points. It was generally true, however, that the greatest offset was at the high end of the scale. As can be seen by comparing Figures 1 and 2, the difference in the HRC values as measured by NIST and U.S. industry at that time coincides with the measurement difference between the U.S. and the majority of other countries participating in the 1983 OIML intercomparison.

5. EC Comparison – 1999

At the 1995 meeting of the International Organization for Standardization (ISO) committee TC 164 /SC 3 on Hardness Testing (of metals), a resolution (No. 158) was passed stating the need for worldwide unified Rockwell hardness scales that use a diamond indenter. The resolution proposed that a test program be initiated to investigate the measurement differences between countries. The desired outcome of the resolution was to determine the sources of the

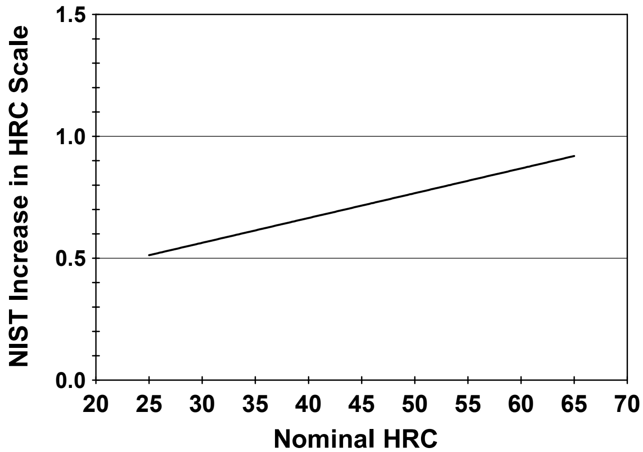

Figure 2. General trend of the difference between NIST and U.S. industry Rockwell C scales. The line represents the approximate increase in the HRC scale as determined by NIST (for hardness levels as indicated on the bottom axis) with respect to the HRC scale used by U.S. industry prior to development of the NIST scale.

measurement differences, leading to a solution for standardizing Rockwell hardness worldwide. In 1996, the European Community (EC) funded an intercomparison of the National Measurement Institutes (NMIs) of countries engaged in the standardization of Rockwell hardness [10,11]. The intercomparison was limited to the Rockwell hardness scales that use a diamond indenter; i.e., HRA, HRC, HCD, HR15N, HR30N and HR45N. Although the EC funded this study, non-European countries were also allowed to participate. In the end, thirteen Rockwell standardization facilities participated, including NIST as the hardness NMI for the United States. The study was coordinated by Materialprüfungsamt Nordfheinwestfalen (MPA-NRW, Germany).

For this study, three parameters of the Rockwell hardness test were investigated; the effect of each NMI's standardizing machine, the effect of each NMI's standardizing indenter, and the effect of the time that the total force is applied during a test, referred to as the dwell time. These three variables were widely considered to be the major sources of the differences between NMI's measurement values. To reduce the influence of the testing material, each NMI measured a common set of test blocks that were passed from laboratory to laboratory in a "round robin" approach. To investigate the effect of the NMI's standardizing machine, all laboratories made one series of measurements using a common indenter. To investigate the effect of the NMI's standardizing indenter, all laboratories made one series of measurements using their own indenter. In the first two investigations, each laboratory applied the same prescribed testing procedure, or a procedure as close to the prescribed as their equipment would allow. The testing procedure included a total force dwell time of 5.5 s. In a third series of measurements, the effect of the total force dwell time was investigated by using a common indenter and a distinctly different total force dwell time of 15 s. For each of these three series of measurements, the results were initially analyzed by comparing the overall spread in the results of all NMIs.

The intercomparison was completed in 1999. Figures 3 through 8 show the results of each NMI's measurements using their own indenter for each of the six Rockwell diamond indenter scales.

This, in effect, provides an indication of the actual standardizing measurements, which would have been made by each NMI at that time. It should be noted that one stipulation for participation in this intercomparison was that the NMIs would not be identified and that each NMI could choose not to have their measurement results reported. As a result, only the measurements of ten NMIs are shown, and only the United States is identified. By comparing Figure 1 with Figure 3, it can be seen that the majority of NMIs demonstrated better agreement for Rockwell C scale measurements as compared to the OIML intercomparison of 1983. It can also be seen that the United States measurements better agree with the majority of other NMIs now that the standardization of Rockwell hardness is being conducted by NIST. Figures 4

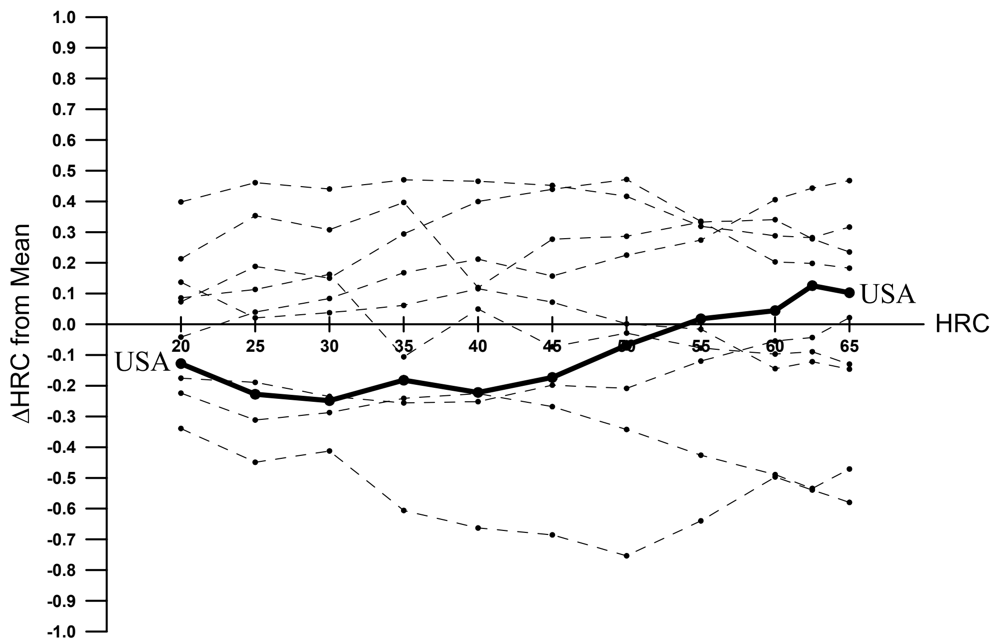

Figure 3. 1999 EC intercomparison of the HRC scale with each laboratory using it's own standardizing indenter and a 5.5 s total force dwell time.

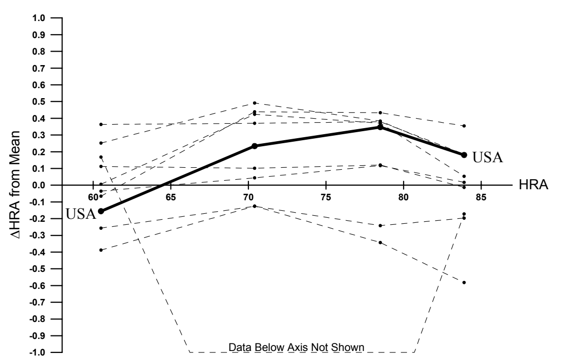

Figure 4. 1999 EC intercomparison of the HRA scale with each laboratory using it's own standardizing indenter.

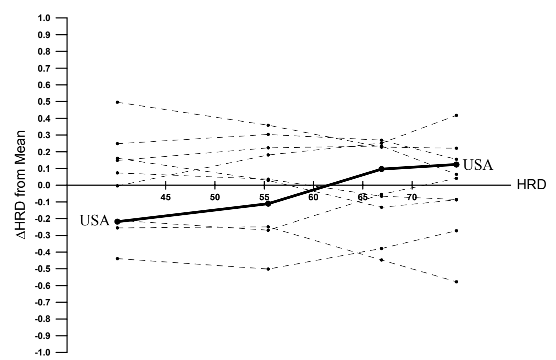

Figure 5. 1999 EC intercomparison of the HRD scale with each laboratory using it's own standardizing indenter.

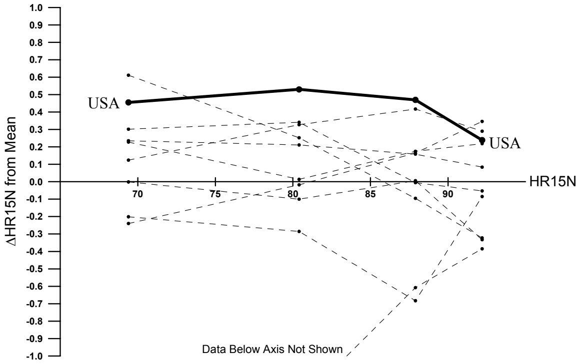

Figure 6. 1999 EC intercomparison of the HR15N scale with each laboratory using it's own standardizing indenter.

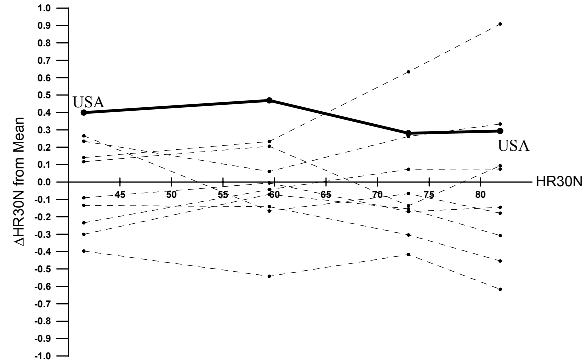

Figure 7. 1999 EC intercomparison of the HR30N scale with each laboratory using it's own standardizing indenter.

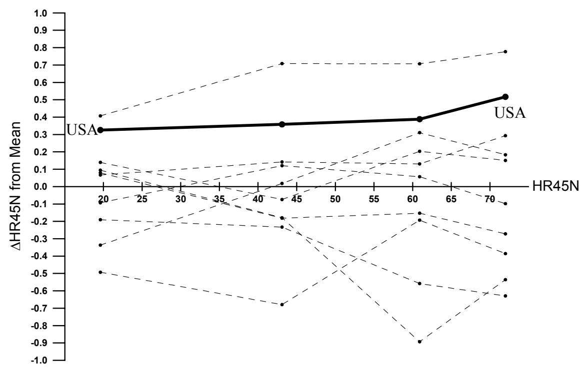

Figure 8. 1999 EC intercomparison of the HR45N scale with each laboratory using it's own standardizing indenter.

through 8 also indicate that the U.S. agrees fairly well with the majority of NMIs for the other Rockwell hardness scales that were investigated, although the U.S. measurements are at the higher hardness edge of the grouping for the Rockwell 'N' scales; i.e., HR15N, HR30N and HR45N.[2]

Two questions can be answered by the results of the remaining comparison measurements. The first question is whether the differences between NMI measurements can be attributed primarily to the use of different designs of standardizing machines (which also results in differing testing procedures), or is it primarily the result of using different diamond indenters, each having a slightly different shape and being manufactured using differing techniques and diamond mounting materials? By comparing the previously discussed HRC results of Figure 3 with HRC measurement results using the common indenter given in Figure 9, it can be seen that the

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[2] The NIST measured Rockwell hardness data presented in Figures 3 through 10 are estimated to have an expanded uncertainty no larger than ±0.1 Rockwell units without incorporating biases due to the indenters used, which are unknown. The NIST expanded uncertainty is calculated as $U = ku_c$ where u_c is the combined standard uncertainty and k, the coverage factor, is taken as 2. The uncertainty of data from the other laboratories is unknown.

majority of NMIs exhibited closer agreement when using the common indenter. This would imply that the diamond indenters used by the hardness standardizing NMIs must be standardized in some manner to an internationally accepted common measurement performance.

The second question is whether a short or long total-force dwell time can provide better agreement between NMIs? During the total-force dwell time of a Rockwell hardness test, a constant force is maintained on the indenter. Because most materials will creep under load, the indenter continues to penetrate into the material. The rate of penetration is rapid at the start of the dwell time and diminishes as time goes by. Since Rockwell hardness is related to depth of penetration, the hardness result varies with differing dwell times. It was speculated that, by using a longer dwell time, the rate of penetration due to material creep would become small. This would result in more consistency in the measurement of indentation depths, and thus better agreement in the hardness values between laboratories. The problem with using longer dwell times is that it increases the time to make a hardness test, something that is typically undesirable to industry. By comparing the previously discussed HRC results of Figure 9, where a 5.5 s dwell time was used, with the HRC measurement results given in Figure 10, where a longer 15 s dwell time was used, it can be seen that there was surprisingly better agreement between the majority of NMIs when the shorter 5.5 s dwell time was used.

6. The Working Group on Hardness of the BIPM

Although the agreement between the world's NMIs has improved since 1983, the current

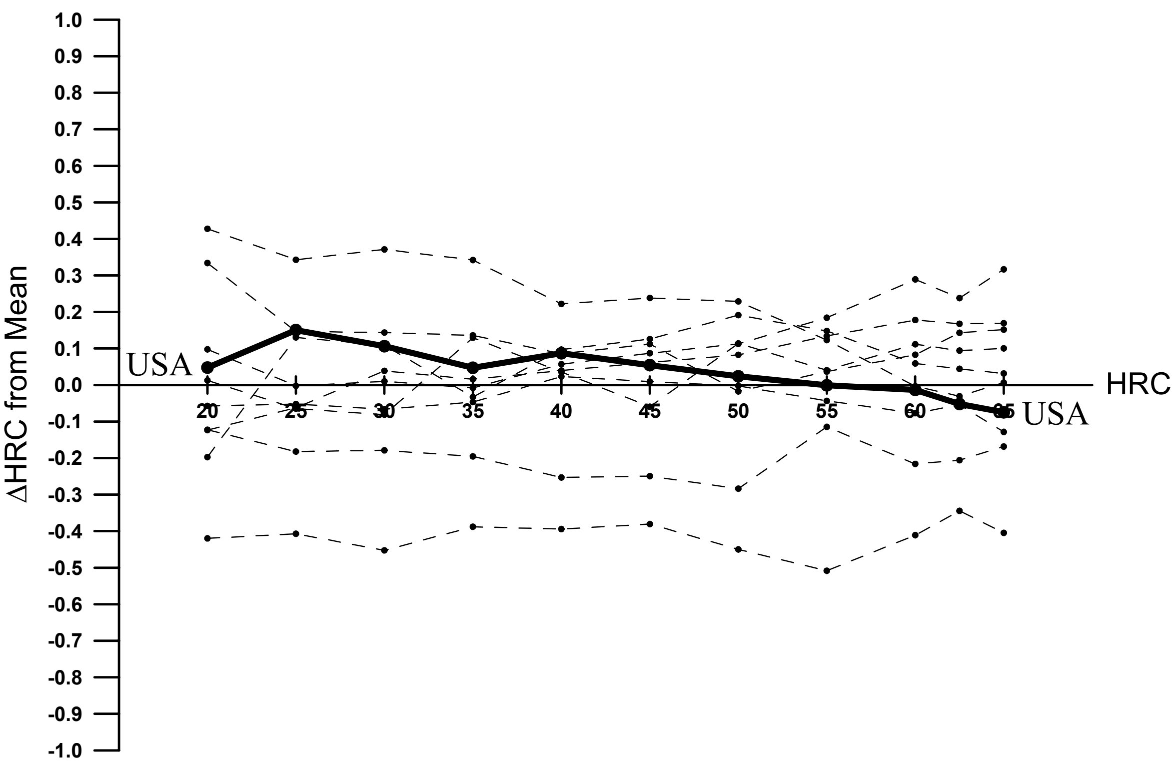

Figure 9. 1999 EC intercomparison of the HRC scale with each laboratory using a common indenter and a 5.5 s total force dwell time.

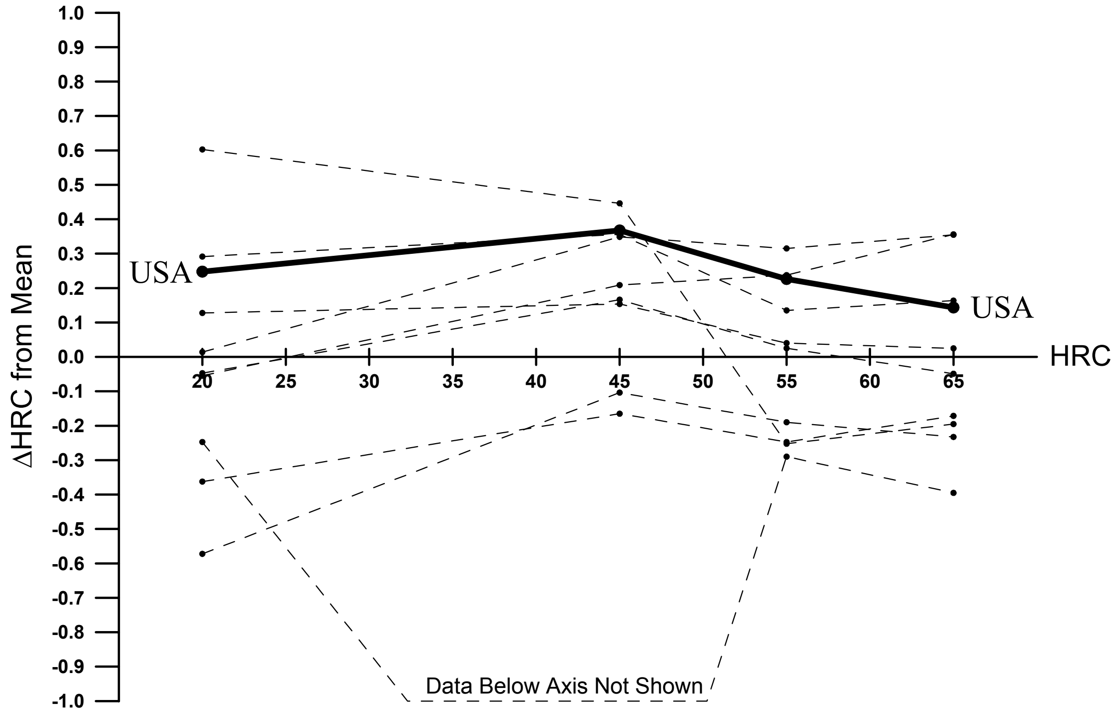

Figure 10. 1999 EC intercomparison of the HRC scale with each laboratory using a common indenter and a 15 s total force dwell time.

magnitude of the differences continues to prevent Rockwell hardness from being characterized as internationally harmonized. The differences continue to be significant. For example, the range of differences between NMIs for measurements above 60 HRC is approximately equal to the acceptability range specified by ISO [12] and ASTM [2] for calibrating a Rockwell testing machine in industry. These findings prompted the NMIs involved with the standardization of hardness to propose and organize a "Working Group on Hardness", which, in 1999, was designated as the official Working Group on Hardness (WGH) of the Consultative Committee on Mass (CCM) under the International Bureau of Weights and Measures (BIPM) [13]. An important task currently being undertaken by the WGH is the development of a distinct definition for Rockwell hardness by defining specific values for each test parameter, in contrast to the current allowable ranges permitted by test method standards. It is believed that if all NMIs were to adhere to the same well-defined procedure when performing Rockwell hardness standardizations, the sources of bias related to the testing procedure should be reduced providing better measurement consistency between countries.

7. Indenter Measurement Key Comparison

The 1999 EC intercomparison, discussed previously, confirmed that the diamond indenter is a major source of the differences in Rockwell hardness measurements. There have been many scientific studies investigating the effect of the diamond indenter on the Rockwell hardness test result [e.g., 14,15,16,17]. A new task being undertaken by the WGH is to develop a strategy for standardizing Rockwell diamond indenters used by NMIs in order to reduce this source of measurement bias. An effort will be made to acquire a selection of “metrological” Rockwell diamond indenters for use by the NMIs. In order to accomplish this goal, it will be necessary to perform geometrical and performance comparisons of the indenters in multiple laboratories. Before the geometrical comparisons can be made, the capabilities of the measurement laboratories must be known. A key-comparison is planned for the systems and techniques used by NMIs to measure the geometrical parameters of the Rockwell diamond indenter. The participating institutes for this comparison will be Istituto di Metrologia G. Colonnetti (IMGC, Italy), MPA-NRW (Germany), NIST (U.S.), Physikalisch-Technische Bundesanstalt (PTB, Germany), and possibly the National Research Laboratory of Metrology (NRLM, Japan), National Physical Laboratory (NPL, U.K.), Korea Research Institute of Standards and Science (KRISS, Korea), Centro Nacional de Metrologia (CENAM, Mexico) and Office Fédéral de Métologie (OFMET, Switzerland). The comparison is scheduled to start this year with the IMGC being the pilot institute.

8. Summary

The importance of the United States participation in the 1983 and 1999 world intercomparisons of Rockwell hardness is quite clear. The 1983 intercomparison highlighted the fact that the commercially maintained Rockwell C hardness scale was significantly different from the majority of other countries standardizing hardness. That fact helped initiate the development of the NIST Rockwell hardness standardization program that has brought the U.S. HRC scale in line with other NMIs. This alignment was confirmed by the second world comparison in 1999.

The 1999 world comparison has provided valuable insight into the sources of bias between the world’s NMIs that standardize Rockwell hardness. The results have shown that:

1. The diamond indenter is currently a significant source of measurement bias.

2. The different designs of standardizing machines and varied testing procedures also significantly effect the Rockwell hardness standardization.

3. The total force dwell time need not be increased to improve the measurement consistency, allowing the standardization test to be more consistent with industry practice.

It is apparent that with the improvements to hardness testing equipment over the past 20 years, the current capability of Rockwell hardness has advanced from simply a “measurement tool” to allow the possibility of hardness as a “metrological measurement.” Even so, the latest worldwide intercomparison of the world’s highest-level hardness standardizing laboratories has demonstrated that improvements are still needed before Rockwell hardness will be truly harmonized to an acceptable level. The NMI’s hardness standardizing laboratories have recognized this, and are currently working towards a solution through a working group of the BIPM.

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