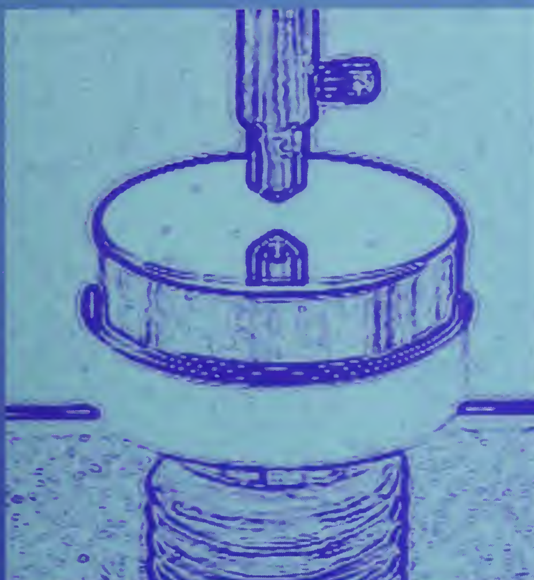
e guide

recommended

Rockwell Hardness Measurement of Metallic Materials



Samuel R. Low

NIST
ational Institute of
tandards and Technology
chnology Administration
S. Department of Commerce

Special Publication 960-5

NIST Recommended Practice Guide

Special Publication 960-5

Rockwell Hardness Measurement of Metallic Materials

Samuel R. Low

Materials Science and
Engineering Laboratory

January 2001

U.S. Department of Commerce
Donald L. Evans, Secretary

Technology Administration
Karen H. Brown, Acting Under Secretary of
Commerce for Technology

National Institute of Standards and Technology
Karen H. Brown, Acting Director

Certain commercial entities, equipment, or materials may be identified in this document in order to describe an experimental procedure or concept adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the entities, materials, or equipment are necessarily the best available for the purpose.

National Institute of Standards and Technology
Special Publication 960-5
Natl. Inst. Stand. Technol.
Spec. Publ. 960-5
116 pages (January 2001)
CODEN: NSPUE2

U.S. GOVERNMENT PRINTING OFFICE
WASHINGTON: 2000

For sale by the Superintendent of Documents
U.S. Government Printing Office
Internet: bookstore.gpo.gov Phone: (202) 512–1800 Fax: (202) 512–2250
Mail: Stop SSOP, Washington, DC 20402-0001

FOREWORD

The Rockwell hardness test continues to be applied as a tool for assessing the properties of a product while the tolerances on the acceptable material hardness have become tighter and tighter. Adhering to "good practice" procedures when performing Rockwell hardness measurements and calibrations is a beneficial step to reducing measurement errors. The purpose of this Guide is to explain the causes of variability in Rockwell hardness test results and to supplement the information given in test method standards with good practice recommendations. Although this Guide is directed more towards the users of Rockwell hardness having the greatest concern for accuracy in their measurements, much of the information given is also applicable for users that only require test results to be within wide tolerance bands, where high accuracy is not as critical.

More information on the SP 960 series can be found on the internet at **http;//www.nist.gov/practiceguides**. This web site includes a complete list of NIST Pratice Guides and ordering information.

ACKNOWLEDGMENTS

The author would like to thank the following persons for sharing their experience and providing information for this Guide. Their input and review has provided a link to the practical world of Rockwell hardness testing.*

T. Robert Shives, Consultant

Richard Antonik, SUN-TEC Corporation

Robert A. Ellis and *Richard A. Ellis*, David L. Ellis Co., Inc.

Thomas P. Farrell, Mitutoyo America Corporation

Giancarlo Mazzoleni and *Douglas B. McGhee*, Newage Testing Instruments, Inc.

Michael L. Milalec and *Richard J. Snow*, Gilmore Diamond Tools, Inc.

Paul M. Mumford, United Calibration Corporation

Edward L. Tobolski, Wilson Division of Instron Corporation

The author would also like to thank present and former NIST co-workers James L. Fink, Carole D. Flanigan, Robert J. Gettings, Walter S. Liggett, Jr., David J. Pitchure, John H. Smith, and John Song for their contributions towards the Rockwell hardness standardization program at NIST.

* The acknowledgements of the persons and companies listed above should not be interpreted as an endorsement by NIST of their products or services.

List of Figures

List of Tables

1 INTRODUCTION

Working in a ball-bearing manufacturing plant in 1919, Stanley P. Rockwell invented the Rockwell hardness test as a tool for obtaining a rapid and more accurate measure of the hardness of ball races(1). Soon after, Charles H. Wilson expanded on Rockwell's invention, and he advanced the Rockwell hardness test into what is today the most widely used method for acceptance testing and process control of metals and metal products. Since its development, the popularity of the Rockwell hardness test has steadily grown. The Rockwell hardness test continues to be applied as a tool for assessing the properties of a product while the tolerances on the acceptable material hardness have become tighter and tighter. The once-thought-of manufacturing tool has developed into a metrological instrument. To achieve meaningful measurement results in these circumstances, it is important that the user make every effort to reduce measurement errors. This is more easily accomplished when the influences contributing to the error in a Rockwell hardness test are known, and there is an understanding of what can be done to reduce these errors. Adhering to "good practice" procedures when performing Rockwell hardness measurements and calibrations is a crucial step to reducing measurement errors.

The purpose of this Guide is not to specify the requirements for conducting a Rockwell hardness test. Test method standards published by national and international standards writing organizations, such as the American Society for Testing and Materials (ASTM) and the International Standards Organization (ISO), provide specific requirements and procedures for Rockwell hardness testing. The intention of this Guide is to explain the causes of variability in Rockwell hardness test results and to supplement the information given in test method standards with good practice recommendations. Although this Guide is directed more towards the users of Rockwell hardness having the greatest concern for accuracy in their measurements, much of the information given is also applicable for users that only require test results to be within wide tolerance bands, where high accuracy is not as critical. It is recognized that Rockwell hardness is often used for testing non-metallic materials such as plastics; however, this Guide is primarily applicable to the testing of metallic materials.

This Guide also provides recommendations for conducting verifications of Rockwell hardness machines based on the procedures specified by the test method standards. Some procedures recommended by this Guide exceed current requirements of the test methods; however, they can be very useful in helping to determine and limit sources of measurement error.

2 ROCKWELL HARDNESS TEST

2.1 Significance of the Test

The Rockwell hardness test is an empirical indentation hardness test. Its worldwide adoption has likely resulted from the many advantages provided by the test method. The test is fast, inexpensive, and relatively non-destructive, leaving only a small indentation in the material. The simplicity in the operation of a Rockwell hardness machine has provided the added advantage that Rockwell hardness testing usually does not require a highly skilled operator. By way of correlation with other material properties, the Rockwell hardness test can provide important information about metallic materials, such as the tensile strength, wear resistance, and ductility. The test is generally useful for material selection, for process and quality control, and for acceptance testing of commercial products. Consequently, in today's manufacturing facilities, Rockwell hardness machines can be found in use in almost every testing environment, from the hot, oily surroundings of some manufacturing facilities, to environmentally controlled metallographic and calibration laboratories.

2.2 Rockwell Indentation Test Principle

The Rockwell hardness test is one of several common indentation hardness tests used today, other examples being the Brinell hardness test and Vickers hardness test. Most indentation hardness tests are a measure of the deformation that occurs when the material under test is penetrated with a specific type of indenter. In the case of the Rockwell hardness test, two levels of force are applied to the indenter at specified rates and with specified dwell times, as illustrated for the Rockwell C scale (HRC) test in Figure 1. Unlike the Brinell and Vickers tests, where the size of the indentation is measured following the indentation process, the Rockwell hardness of the material is based on the difference in the depth of the indenter at two specific times during the testing cycle, indicated by the **X** marks in Figure 1. The value of hardness is calculated using a formula that was derived to yield a number falling within an arbitrarily defined range of numbers known as a Rockwell hardness scale. 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.

The general Rockwell test procedure is the same regardless of the Rockwell scale or indenter being used. The indenter is brought into contact with the material to be tested, and a preliminary force (formally referred to as the minor load) is applied to the indenter. The preliminary force is usually held constant for a set period of time (dwell time), after which the depth of indentation is measured. After the measurement is made, an additional amount of force is

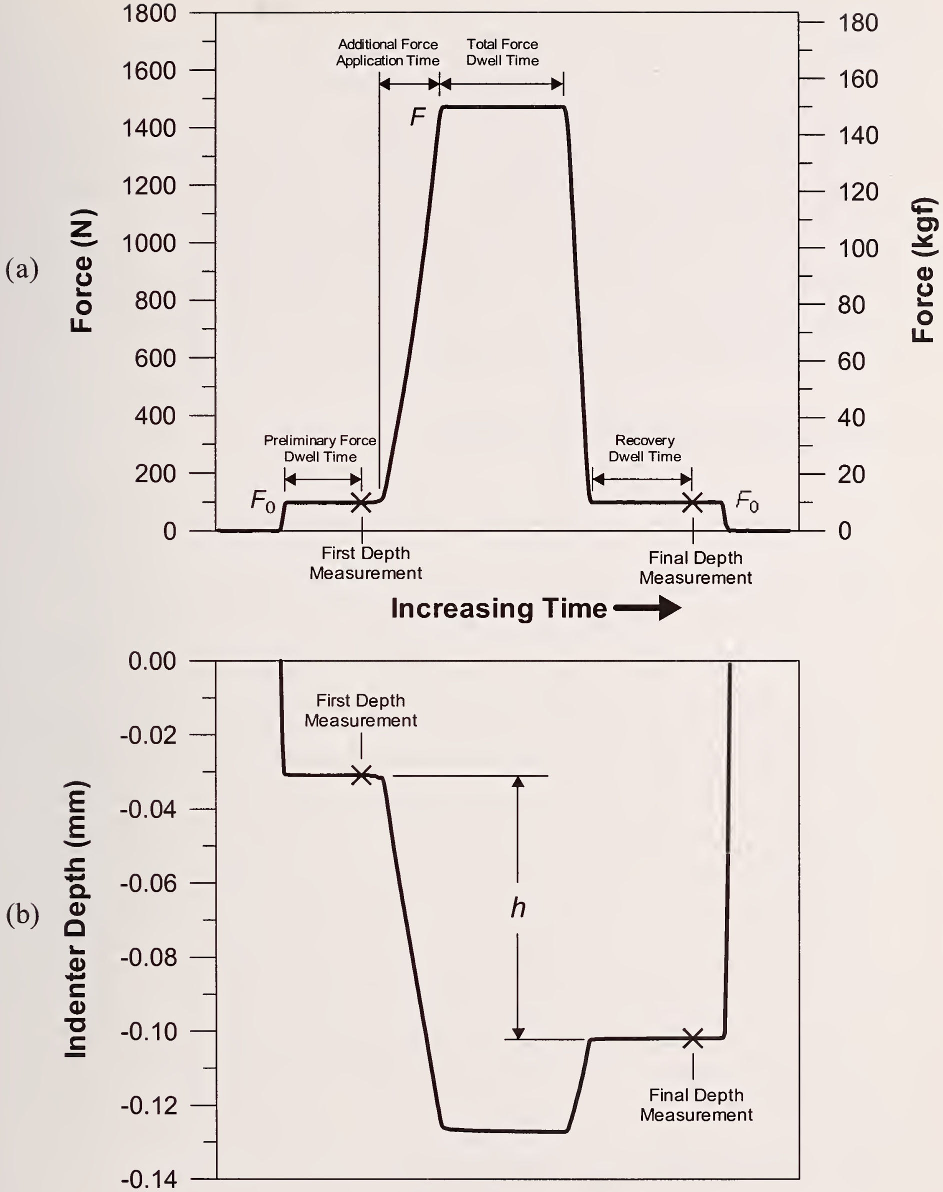


Figure 1.

Plots of force vs. time (a) and indenter-depth vs. time (b) for an HRC test illustrating the testing cycle parts and the difference in indenter depth measurements *h*.

applied at a set rate to increase the applied force to the total force level (formally referred to as the major load). The total force is held constant for a set time period, after which the additional force is removed, returning to the preliminary force level. After holding the preliminary force constant for a set time period, the depth of indentation is measured for a second time, followed by removal of the indenter from the test material. The measured difference between the first and second indentation depth measurements, h, (see Figure 1) is then used to calculate the Rockwell hardness number. For many older models of Rockwell hardness machines, the operator must manually control most or all of the steps of the test procedure. Many of today's newer machines automatically perform the entire Rockwell test.

2.3 Rockwell Hardness Scales

Many manufactured products are made of different types of metals and alloys varying in hardness, size, and thickness. To accommodate the testing of these diverse products, several different indenter types (as discussed in 3.3.8) were developed for the Rockwell test to be used in conjunction with a range of standard force levels. Each combination of indenter type and applied force levels has been designated as a distinct Rockwell hardness scale. The ASTM(2) defines thirty different Rockwell scales, as shown in Table 1. Rockwell hardness scales are divided into two categories: regular Rockwell scales and superficial Rockwell scales. Both categories of tests use the same types of indenters. The regular Rockwell scales employ the heavier force levels. For these scales, the preliminary force level is 98.07 N (10 kgf), and the standard total force levels may be 588.4 N (60 kgf), 980.7 N (100 kgf) or 1471 N (150 kgf). The superficial Rockwell scales employ lighter force levels, typically for use on thinner materials. For the superficial Rockwell scales, the preliminary force level is 29.42 N (3 kgf), and the standard total force levels may be 147.1 N (15 kgf), 294.2 N (30 kgf) or 441.3 N (45 kgf). Table 1 provides typical applications for the different Rockwell scales as recommended by ASTM(2), and it lists the appropriate type of indenter and force levels to be used with the particular scale.

2.4 Rockwell Hardness Number

A Rockwell hardness measurement is reported as a Rockwell hardness number, without units. The Rockwell hardness number is calculated from the difference in the indentation depths before and after application of the total force, while maintaining the preliminary test force. The difference in indentation depths is measured as h as described above. The calculation of the Rockwell hardness number is dependent on the specific combination of indenter type and the forces that are used.

Table 1.

Rockwell hardness scales with the corresponding indenter type, applied forces and typical applications

	Scale Symbol	Indenter Type (Ball dimensions indicate diameter.)	Preliminary Force N (kgf)	Total Force N (kgf)	Typical Applications
Regular Rockwell Scales	A	Spheroconical Diamond	98.07 (10)	588.4 (60)	Cemented carbides, thin steel, and shallow case hardened steel.
	B	Ball - 1.588 mm (1/16 in.)	98.07 (10)	980.7 (100)	Copper alloys, soft steels, aluminum alloys, malleable iron, etc.
	C	Spheroconical Diamond	98.07 (10)	1471 (150)	Steel, hard cast irons, pearlitic malleable iron, titanium, deep case hardened steel, and other materials harder than HRB 100.
	D	Spheroconical Diamond	98.07 (10)	980.7 (100)	Thin steel and medium case hardened steel, and pearlitic malleable iron
	E	Ball - 3.175 mm (1/8 in.)	98.07 (10)	980.7 (100)	Cast iron, aluminum and magnesium alloys, and bearing metals
	F	Ball - 1.588 mm (1/16 in.)	98.07 (10)	588.4 (60)	Annealed copper alloys, and thin soft sheet metals.
	G	Ball - 1.588 mm (1/16 in.)	98.07 (10)	1471 (150)	Malleable irons, copper-nickel-zinc and cupro-nickel alloys.
	H	Ball - 3.175 mm (1/8 in.)	98.07 (10)	588.4 (60)	Aluminum, zinc, and lead.
	K	Ball - 3.175 mm (1/8 in.)	98.07 (10)	1471 (150)	Bearing metals and other very soft or thin materials. Use smallest ball and heaviest load that does not give anvil effect.
	L	Ball - 6.350 mm (1/4 in.)	98.07 (10)	588.4 (60)	
	M	Ball - 6.350 mm (1/4 in.)	98.07 (10)	980.7 (100)	
	P	Ball - 6.350 mm (1/4 in.)	98.07 (10)	1471 (150)	
	R	Ball - 12.70 mm (1/2 in.)	98.07 (10)	588.4 (60)	
	S	Ball - 12.70 mm (1/2 in.)	98.07 (10)	980.7 (100)	
	V	Ball - 12.70 mm (1/2 in.)	98.07 (10)	1471 (150)	
Superficial Rockwell Scales	15N	Spheroconical Diamond	29.42 (3)	147.1 (15)	Similar to A, C and D scales, but for thinner gage material or case depth.
	30N	Spheroconical Diamond	29.42 (3)	294.2 (30)	
	45N	Spheroconical Diamond	29.42 (3)	441.3 (45)	
	15T	Ball - 1.588 mm (1/16 in.)	29.42 (3)	147.1 (15)	Similar to B, F and G scales, but for thinner gage material.
	30T	Ball - 1.588 mm (1/16 in.)	29.42 (3)	294.2 (30)	
	45T	Ball - 1.588 mm (1/16 in.)	29.42 (3)	441.3 (45)	
	15W	Ball - 3.175 mm (1/8 in.)	29.42 (3)	147.1 (15)	Very soft material.
	30W	Ball - 3.175 mm (1/8 in.)	29.42 (3)	294.2 (30)	
	45W	Ball - 3.175 mm (1/8 in.)	29.42 (3)	441.3 (45)	
	15X	Ball - 6.350 mm (1/4 in.)	29.42 (3)	147.1 (15)	
	30X	Ball - 6.350 mm (1/4 in.)	29.42 (3)	294.2 (30)	
	45X	Ball - 6.350 mm (1/4 in.)	29.42 (3)	441.3 (45)	
	15Y	Ball - 12.70 mm (1/2 in.)	29.42 (3)	147.1 (15)	
	30Y	Ball - 12.70 mm (1/2 in.)	29.42 (3)	294.2 (30)	
	45Y	Ball - 12.70 mm (1/2 in.)	29.42 (3)	441.3 (45)	

For scales that use a spheroconical diamond indenter, the Rockwell hardness number is calculated from *h* (in mm) as:

$$Regular\ Rockwell\ \ Hardness = 100 - \frac{h}{0.002\,mm}$$

$$Rockwell\ Superficial\ Hardness = 100 - \frac{h}{0.001\,mm}.$$

For scales that use a ball indenter, the Rockwell hardness number is calculated from h (in mm) as:

$$Regular\ Rockwell\ \ Hardness = 130 - \frac{h}{0.002\,mm}$$

$$Rockwell\ Superficial\ Hardness = 100 - \frac{h}{0.001\,mm}.$$

2.5 Test Method Standards

The Rockwell hardness test method is specified by several national and international standards. In North America, most Rockwell hardness testing is performed in accordance with standards published by the ASTM[(2)]. In other countries throughout the world, industry testing may be in accordance with a nationally published standard, but increasingly, countries are adopting the ISO Rockwell hardness standards[(3,4,5)]. The International Organization of Legal Metrology (OIML) publishes Rockwell hardness documents referred to as *International Recommendations*[(6,7,8,9)] for countries desiring to regulate Rockwell hardness testing for legal purposes. Presently, use of the OIML documents is very meager. Listed below are the document standards specifying requirements for Rockwell hardness testing, as well as other documents related to Rockwell hardness testing.

2.5.1 ASTM

ASTM E 18 – 2000, Standard Test Methods for Rockwell Hardness and Rockwell Superficial Hardness of Metallic Materials

Related ASTM standards:

ASTM E 110 – 82 (Reapproved 1997), Standard Test Method for Indentation Hardness of Metallic Materials by Portable Hardness Testers

ASTM E 140 – 97, Standard Hardness Conversion Tables for Metals

To contact or order documents:

ASTM
100 Barr Harbor Drive
West Conshohocken, PA 19428-2959
Phone: (610) 832–9585 Fax: (610) 832–9555
E-mail: service@astm.org
http://www.astm.org

ASTM standards can be purchased in the Store area of the ASTM web site. Using a credit card, you can download standards to your own computer; receive standards by fax, or by traditional mail. Standards vary in cost, based on their length. Average cost for an ASTM standard is about $25. A subscription service is also offered where subsets of standards can be accessed for a set fee. Standards can also be purchased from ASTM by contacting ASTM's Customer Service Department at (610) 832–9585, Monday through Friday, 8AM-5PM Eastern Time.

2.5.2 ISO

ISO 6508-1 Metallic Materials – Rockwell hardness test (scales A, B, C, D, E, F, G, H, K, N, T) – Part 1: Test method, 1999-09-01

ISO 6508-2 Metallic Materials – Rockwell hardness test (scales A, B, C, D, E, F, G, H, K, N, T) – Part 2: Verification of testing machines, 1999-09-01

ISO 6508-3 Metallic Materials – Rockwell hardness test (scales A, B, C, D, E, F, G, H, K, N, T) – Part 3: Calibration of reference blocks, 1999-09-01

To contact or order documents:

American National Standards Institute
11 West 42nd Street
13th floor
US – New York, N.Y. 10036
Telephone: +1 212 642 49 00 Fax: +1 212 398 00 23
E-mail: info@ansi.org
http://www.ansi.org/

Electronic copies of ISO standards may be purchased from ANSI's Electronic Standards Store at the American National Standards Institute web site. Paper copies of ISO standards may be purchased from Global Engineering Documents as follows:

Global Engineering Documents
Phone: 800–854–7179 or 303–397–7956
Fax: 303–397–2740
Email: global@ihs.com
http://www.global.ihs.com

2.5.3 OIML

OIML International Recommendation No. 11 (1974), Verification and calibration of "Rockwell B" hardness standardized blocks

OIML International Recommendation No. 12 (1974), Verification and calibration of "Rockwell C" hardness standardized blocks

OIML International Recommendation No. 36 (1976), Verification of indenters for hardness testing machines (Systems: Brinell – Rockwell B, F, and T – Vickers – Rockwell C, A, and N)

OIML International Recommendation No. 39 (1981), Verification of hardness testing machines (Rockwell B, F, T - C, A, N systems

To contact or order documents:

OIML Publications may be purchased (in French and in English in most cases) from the Organization's Secretariat (BIML).

Bureau International de Métrologie Légale
11, rue Turgot
F-75009 Paris
France
Tel.: +33 (0) 1 48 78 12 82 and 42 85 27 11 Fax: +33 (0) 1 42 82 17 27
E-mail: biml@oiml.org
http://www.oiml.org/

3 TEST PROCEDURE

Numerous aspects of the Rockwell hardness test can influence the measurement result. These include the function and calibration of individual components of the hardness machine, variations in the indenter, the testing cycle that is used, the testing environment, the condition of the test material, and the operator. When considering all of these influences, it seems remarkable that the Rockwell test has provided such a reliable test throughout its long usage. Much of the test's reliability may be attributed to the common practice of performing periodic verifications of the testing machine, often several times during a day.

When a high level of accuracy is important, it is usually necessary to put more effort into a measurement process than is specified by test method standards[10]. As with any method of measurement, it is beneficial to identify the significant sources of error in a Rockwell hardness measurement so that an attempt can be made to reduce the errors and, thus, improve accuracy. Through an understanding of how the various test influences can affect a Rockwell hardness measurement, it becomes evident that a considerable difference in hardness results can be obtained for the same test sample merely by varying one or more of the test parameters. The difference in test results can be significant, even while remaining within the individual parameter tolerances specified by test method standards. It is also likely that many Rockwell machines are adjusted to offset one error with another error in order to correctly measure reference standards.

The ASTM and ISO test method standards specify the general procedures to use when performing a Rockwell hardness test. In addition, the instruction manual supplied with most testing machines normally provides supplementary details on specific operational procedures. This section will discuss procedures and precautions to be applied to general Rockwell hardness testing. It will not cover specialized procedures for testing the vast varieties of materials and part geometries for which Rockwell hardness may be used. It should be noted that there are many specialized fixtures, indenters, anvils, and testing machine configurations that are commercially available for the testing of large parts, long parts, inner surfaces, curved surfaces, and other complex shaped parts[1,11,12,13]. This section will also discuss several of the more significant sources of error of the Rockwell hardness test. These include the influences of the hardness machine, indenters, testing cycle, testing environment, and other factors that may affect the reproducibility of the test.

3.1 Choosing the Appropriate Rockwell Scale

The ASTM specifies thirty different Rockwell scales, each employing a different combination of test forces and indenter types, which allows the testing of most types of metallic materials and products. When Rockwell hardness is called out by a product standard or specification, the choice of scale is usually specified. In situations where the user must choose the appropriate Rockwell scale, there are several factors that should be considered. These include the type of test material, the test material thickness, the test material area or width, the test material homogeneity, and the limitations of each Rockwell scale.

3.1.1 Type of Test Material

Table 1 lists the typical types of materials that are suitable for testing on each of the thirty Rockwell hardness scales. When deciding on an appropriate Rockwell scale for a particular material, information in this table can assist the user in narrowing down the number of scales to choose from.

3.1.2 Test Material Thickness

As a Rockwell hardness measurement is being made, the material surrounding the indentation is plastically deformed with the deformation extending well below the indentation depth. If the deformation extends completely through the thickness of thin test material, then the deformed material will flow at the interface with the supporting anvil. This will influence the deformation process likely causing the test to give erroneous hardness results. Thus, the test material must have a sufficient thickness in order to obtain a valid Rockwell test value. Similarly, for products that are manufactured to a specific thickness, a Rockwell scale having the appropriate combination of test forces and indenter size must be chosen based on that thickness.

When the approximate hardness of the test material is known, the minimum thickness needed to obtain valid Rockwell measurements may be estimated from data tables and graphs available in the literature, such as in the ASTM standard[(2)]. In general, the zone of deformation extends no more than 10 times the depth of indentation for a diamond indenter test and 15 times the depth of indentation for a ball indenter. As a rule, there should be no deformation on the support side of the test material following a Rockwell test, although such markings are not always indicative of a bad test.

⃠ Testing Precautions

- Testing of too thin material can damage a steel anvil by marring the surface or producing a small indentation. In either case, further testing should not continue with the damaged anvil.
- Stacking one or more additional layers of metallic material together cannot make up for an insufficient material thickness. The material flow between the layers will produce inaccurate measurements.

- If the objective of the Rockwell test is to measure the hardness of a surface feature such as a case-hardened surface, the scale chosen should be based on the thickness of this surface feature.

3.1.3 Test Material Area (or Width)

In the same way that the deformation extends below an indentation, thus limiting the minimum material thickness, the deformation also extends outward through the material width. If a Rockwell measurement is made near the edge of the test material, the deformation surrounding the indentation may extend to the edge and push out the material, thus lowering the measured hardness value. This effect is more significant for softer materials. The general rule as specified by the test method standards is that the distance between the center of an indentation and the edge of the material must be at least 2½ times the diameter of the indentation. The ISO test method standard(3) also specifies that the distance must not be less than 1 mm. Therefore, in cases where Rockwell hardness testing is to be made on narrow width material or material having a small area size, a Rockwell scale must be chosen that produces indentations small enough to prevent this edge interaction.

3.1.4 Test Material Homogeneity

The size and location of metallurgical features in the test material should be considered when choosing the Rockwell scale. For materials that are not homogeneous, an appropriate Rockwell scale should be chosen that would produce a sufficiently large indentation to obtain a hardness value representative of the material as a whole. Also keep in mind that the area surrounding a Rockwell indentation also affects the test result (see above discussions). If the deformation zone surrounding a Rockwell indentation extends into adjacent regions of a differing hardness, such as the heat affected zone of a weld, the test measurement may be influenced. In such cases, a Rockwell scale should be chosen that uses test forces and indenters that produce a small enough indentation to avoid the influence of these areas.

3.1.5 Scale Limitations

Each Rockwell scale is an arbitrarily defined range of numbers from 0 to 100† covering a specific range of material hardness. Although, theoretically, the entire scale can be used for hardness testing, there are practical limitations on the range of testing for many of the Rockwell scales. At the low hardness end of the scales, these limits result from the indenter penetrating too deeply into the material, possibly causing contact with the indenter cap for ball indenters.

† Regular Rockwell scales using a ball indenter hypothetically could obtain Rockwell values greater than 100 up to 130.

In the case of diamond indenters, the sensitivity of the test diminishes as the diamond indenter penetrates further down the conical portion of the diamond. At the high hardness end of the scales, these limits result from the likelihood of fracturing or significantly reducing the life of a diamond indenter. In the case of ball indenters, the sensitivity of the test diminishes, and there is increased possibility of flattening a steel indenter ball. The ISO standard[(3)] suggests the limits given in Table 2 for some Rockwell scales.

Table 2.

Ranges of Rockwell scales given in ISO standards

Recommended Ranges of Rockwell Scales	
20 to 88 HRA[A]	70 to 94 HR15N
20 to 100 HRB[B]	42 to 86 HR30N
20 to 70 HRC	20 to 77 HR45N
40 to 77 HRD	67 to 93 HR15T
70 to 100 HRE	29 to 82 HR30T
60 to 100 HRF	1 to 72 HR45T
30 to 94 HRG	
80 to 100 HRH	
40 to 100 HRK	

[A] *Rockwell testing of tungsten carbide commonly produces hardness values above 88 HRA.*

[B] *Rockwell B scale testing is sometimes made on materials in the range of 0 to 20 HRB.*

★ Good Practice Recommendations

- When several Rockwell scales are acceptable for testing a material, generally, the most commonly used scale for the type of material to be tested should be chosen. In cases where this Rockwell scale is not appropriate for the particular application, the scale employing the highest forces may be the best choice. The highest force will produce the largest indentation covering more of the test material, and it will provide a Rockwell hardness value more representative of the material as a whole. Additionally, the highest test forces provide the most sensitivity in Rockwell hardness testing.

- In circumstances where the user wants to compare measurements with previously obtained Rockwell hardness data, the same scale should be chosen as was used for the previous testing as long as a valid test can be obtained. This is preferred to testing on one Rockwell scale and then converting the data to another Rockwell scale by way of conversion tables. Converted data is never as accurate as the original measurement.
- If the approximate hardness of a material is not known, a diamond indenter scale should be tried first. A diamond indenter is not likely to be damaged by penetrating too deeply into a soft material, whereas a ball indenter may be flattened or damaged if the material is too hard.

3.2 Test Surface Preparation

An important feature of the Rockwell hardness test procedure is the use of the preliminary force as part of the testing cycle. Application of the preliminary force acts to push the indenter through minor surface imperfections and to crush residual foreign particles present on the test surface. By establishing a reference beneath the surface prior to making the first depth measurement, it allows testing of materials with slight surface flaws while maintaining much of the test accuracy. Still, as a general rule, the better a test surface is prepared, the more likely the measurement will represent the true Rockwell hardness value of a material.

For the best results, the test surface and the surface in contact with the support anvil should be smooth, flat, and free of oxides, foreign matter, and lubricants. The test surface should be prepared in a manner that will not alter the properties of the test material such as by overheating or cold-working. The test surface should be representative of the material under test. For that reason, surface effects, such as carburization or decarburization, should be removed prior to testing, unless the purpose of the test is to measure these surface features. Similarly, other types of coatings, such as paint, galvanizing, etc., should also be removed prior to testing.

The degree of surface roughness that can be tolerated depends on the force levels to be applied. A finish ground surface is usually sufficient for the Rockwell C scale and for the Rockwell ball scales that apply a force of at least 980.7 N (100 kgf). In general, lighter test forces require better surface finishes. For the superficial scales that use a total force of 147.1 N (15 kgf), a polished surface is usually required.

3.3 Rockwell Hardness Testing Machine

There are many designs of commercially manufactured Rockwell hardness testing machines. The testing machines discussed in this Guide and specified by the referenced test method standards are limited to only those types of machines capable of performing a true "Rockwell indentation hardness test." Sometimes a true Rockwell test cannot be performed due to the size of the part or its configuration. There are other devices and instruments on the market that can be used in many of these situations, which can also report a Rockwell hardness number. However, the measurement methods used by these devices are not in accordance with the Rockwell indentation hardness principle. These devices employ other test principles, such as striker rebound or eddy-current, and make measurements to which a Rockwell number is correlated. These devices may have some advantages, such as portability, but they cannot report a true Rockwell hardness number.

There have been many improvements in the designs of Rockwell hardness testers over the past 50 years. The most significant improvements have been in the manner in which the forces are applied, the manner in which the indentation depth is measured and the hardness value displayed, and in the automation of the testing machine's operation. Remarkably, many of the older designs of Rockwell machines are still in use, so that a brief discussion of the differences may be beneficial.

★ Good Practice Recommendation

Not all Rockwell hardness machines are equal. All machines may be capable of performing a Rockwell hardness test in accordance with the requirements specified in test method standards, but some may be more suitable for your specific needs. When choosing a Rockwell hardness machine, consider factors such as: the accuracy and measurement repeatability that is required; whether versatility in the testing cycle may be required; the required speed of testing; the Rockwell scales that will be used; the required resolution of the hardness number; the size of material normally tested; and the accessories that may be needed.

⃠ Testing Precautions

When using devices that employ measurement methods other than the Rockwell indentation hardness principle, the type of measurement device that was used should be reported with the correlated Rockwell numbers. This information provides the user of the measurement data a better understanding of how the data was obtained.

3.3.1 Scales That Can Be Tested

Because the regular Rockwell and superficial Rockwell tests use distinctly different levels of force and two different resolutions of depth measurement, most Rockwell machines in the past were designed to test only regular scales or superficial scales. This has become less true today as new machine development has produced many Rockwell machines designs that are capable of testing both regular and superficial scales, sometimes referred to as "twin testers" or "combination testers." These machines usually can test all of the different Rockwell scales, and, in some cases, they can also perform other types of hardness tests.

3.3.2 Force Application Mechanism

Since its development, the most common designs of Rockwell machines have applied the preliminary test force by compression of a helical spring, and have applied the total force by dead weights through a force multiplying lever system. With many years of usage, it is not unusual to find that in older machines the preliminary force springs and the knife-edges supporting the total force lever arms have become worn causing errors in the application of the forces.

With the advent of reliable electronically controlled feedback systems, new machine designs have been developed such as machines that apply the forces with a screw-driven device controlled by a load-cell to monitor the applied force. The new designs have the advantage that the testing cycle can be fully controllable, and errors associated with a lever arm or preliminary force spring are eliminated; however, different errors may be introduced associated with the load-cell or electronics. Lever-arm/spring design machines are continually being improved and are in common use today as reliable testing instruments, but the trend of many Rockwell machine manufacturers is towards developing load-cell design machines.

By varying either the preliminary force level or the total force level, different Rockwell hardness measurement values can be obtained for the same material. The reason for this is illustrated in Figure 2A, Figure 2B, Figure 3A, and Figure 3B, which are plots of Rockwell A scale (HRA) test data measured at NIST[(14)]. Figure 2A illustrates the sequence of how the test forces are applied during the HRA test, with the resulting indentation depth shown in Figure 2B. Each figure shows two overlapping HRA tests; the solid line represents a test using the standard preliminary force of 98.07 N (10 kgf), and the dashed line represents a test where the preliminary force was increased to 103.95 N (10.6 kgf). The test having the higher preliminary force (dashed line) resulted in a slightly increased indentation depth at the first application of preliminary force. Changing the preliminary force level appears to have had negligible effect on the remaining part of the hardness test. Thus, an increase in the level of the preliminary force causes an increase in the indentation depth at the first application of preliminary force. This reduces the measurement value,

h, used for the calculation of the Rockwell hardness number and results in a higher hardness value. For the same reasons, a decrease in the level of the preliminary force results in a lower hardness value.

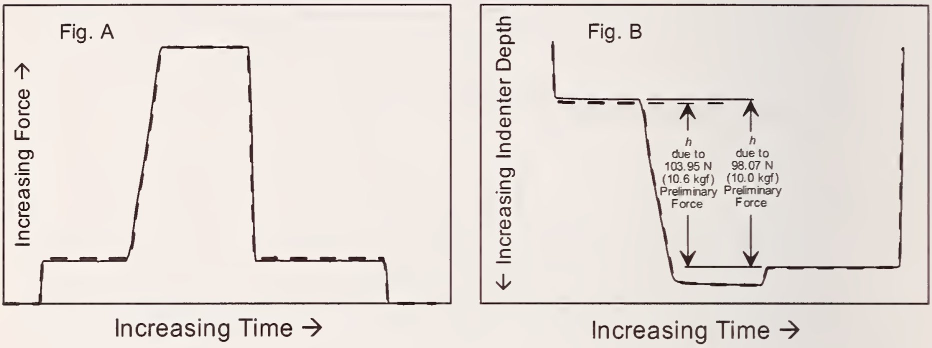


Figure 2.

Force vs. time plot (Figure A) and indenter-depth vs. time plot (Figure B) demonstrating the effect of an increase in the preliminary-force for a Rockwell HRA test.

Figure 3A and Figure 3B illustrate what occurs when the total force level is increased. The test having the higher total force (dashed line) resulted in an increased indentation depth at the application of total force. Following the application of total force, as the additional force is removed returning to the preliminary force level, most of the increased increment in indentation depth is maintained. The increased indentation depth enlarges the measurement value, h, and, thus, results in a lower hardness value. This is the opposite effect of that discussed previously (shown in Figure 2) for an increase in the preliminary force level. Additional tests have shown the two effects to be essentially independent of each other and, therefore, additive in their effect.

The magnitudes of the effects that changes in the preliminary and total forces have on the Rockwell hardness measurement value are given in Appendix A for the Rockwell scales that use a diamond indenter and the Rockwell scales that use a 1.588 mm ($^1/_{16}$ in) diameter ball indenter. Also in Appendix A, data is presented illustrating the magnitude of measurement variation that can be obtained for the Rockwell scales that use a diamond indenter while maintaining the force levels within the ASTM and ISO tolerances. From this data it is seen that a variation of ± 0.5 Rockwell units can easily be achieved for some hardness levels simply by adjusting the force levels within the acceptable tolerance limits.

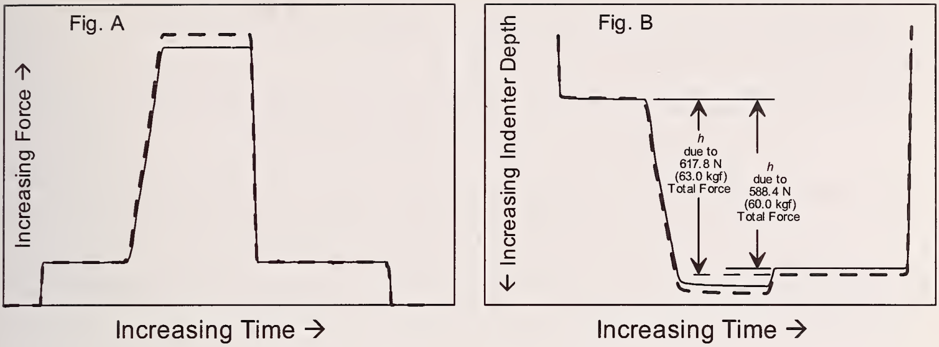


Figure 3.

Force vs. time plot (Figure A) and indenter-depth vs. time plot (Figure B) demonstrating the effect of an increase in the total-force for a Rockwell HRA test.

3.3.3 Depth Measurement; Hardness Value Calculation and Display

The dial indicating-gage was the original method used in Rockwell machines for measuring the indentation depth and for calculating and displaying the Rockwell hardness number. Due to the simplicity of its operation, it continues to be used in some of today's Rockwell machine designs. The general principle of its operation is to mechanically measure the movement of the indenter through a multiplying lever system. The dial face is calibrated to indicate the Rockwell number corresponding to the displacement of the indenter. Usually, the dial divisions have represented whole Rockwell numbers, allowing an estimation of the hardness number to only ½ Rockwell unit. Over years of use, dial gages and lever systems often become worn or misaligned in many machines, adding a component of error to the Rockwell measurement.

Many Rockwell machines produced today use one of several different types of electronic or optical displacement-measuring instruments for directly measuring the depth of indentation. The signal from the measuring instrument is electronically converted to a Rockwell hardness number, which is displayed digitally, sometimes having a resolution of 0.01 Rockwell units. Typically, these new displacement-measuring instruments have a greater accuracy than most dial gage/lever systems, but as often happens with digital displays, showing a number with many decimal places may imply a greater accuracy than is possible with the instrumentation.

The formulas for calculating Rockwell hardness, as given in 2.4 above, directly relate the measured depth of the indenter to the Rockwell hardness number.

Consequently, an error in the depth measurement relates to an error in the hardness measurement result as:

For regular Rockwell scales:	*0.002 mm error in depth = 1 HR unit error.*
For superficial Rockwell scales:	*0.001 mm error in depth = 1 HR unit error.*

Both the ASTM(2) and ISO(4) standards specify that the depth measuring system have an accuracy of at least 0.5 Rockwell numbers.

3.3.4 Manual and Automatic Operation

For many years, most designs of Rockwell hardness machines required that the operator manually apply and remove the preliminary and total forces. This allowed the operator a great deal of control over the testing cycle; however, consistency in the testing cycle varied between operators. The manual operation also was considered to take too much time for production testing.

Eventually, motors were incorporated into Rockwell machine designs to provide an automated and repeatable testing cycle. Some machines were fully automated to drive the application of the forces at a higher rate than was typical for a person. The increased rate of testing is considered important for production testing, but the automated operation removes much of the control by the user. For many of the earlier automatic machines, the operator could not vary the testing cycle. This was good in one respect, it retained consistency from operator to operator; however, the testing cycle was usually set by the manufacturer to complete a test in a relatively short time, with fast force application rates and short dwell times. In following discussions of the Rockwell testing cycle, it will be shown that fast force application rates and short dwell times can lead to poor measurement repeatability.

Recognizing that many testing applications required better measurement repeatability, as well as control of the testing cycle due to varying material plasticity, manufacturers of automatic machines began modifying their designs to allow the operator to adjust the testing cycle. Many of today's Rockwell machines can be set to a "standard" test cycle, while also allowing the testing cycle to be adjusted to better fit the users' needs.

3.3.5 Test Material Support (Anvils)

One of the most important requirements for making a valid Rockwell hardness test is that the test material be well supported to prevent any movement during the test. Even the slightest movement can significantly alter the hardness result. If the test material moves during the test, the movement may be reflected as an error in the depth measurement. Bear in mind that for a Rockwell superficial test, an error in the depth measurement of one-hundredth of a millimeter will produce an error of 10 Rockwell points (see 3.3.3 above).

There are many types of material supports or anvils available for testing different shapes and sizes of test material. The test method standards provide some guidance for selecting an appropriate anvil. In general, flat material should be tested on a flat anvil. Material that is curved should be tested with the convex surface supported on a V-shaped or a double-roller style anvil. Small or thin samples, sheet metal, or parts that do not have flat under-surfaces should be tested on a spot anvil having a small, elevated, flat bearing surface. There are some Rockwell machine designs that apply a clamping force to the test material that is greater than the Rockwell test force. This type of machine is useful when testing larger parts.

★ Good Practice Recommendations

- Often overlooked sources of error in Rockwell testing are the anvil and anvil seat. A dirty anvil seat and almost any perceptible flaw on the anvil and anvil seat, such as scratches or indents, can significantly affect the hardness result. The anvils and the anvil seat should be routinely cleaned and inspected for damage and replaced or reground when damage occurs.
- When testing large samples of test material or material with a long shape that significantly overhangs the hardness machine's anvil support, the material should be additionally supported using suitable outboard fixtures. Otherwise, the overhang may cause a cantilever or lateral force to be applied to the indenter, resulting in measurement error or damage to the indenter. These types of parts should not be supported by hand.
- It is very important that the method used to attach an anvil to a Rockwell machine prevents any rocking or other movement of the anvil during the test. Many Rockwell machine designs attach the anvil by inserting its base into a slip fitting. This design is suitable for most purposes, although for critical applications, it may be beneficial to rigidly affix the anvil to the testing machine.
- Each time an anvil is installed, regardless of its design, it must be adequately seated to the testing machine by making repeated hardness tests on a uniform piece of material, such as a test block. Repeat the tests until there is no increasing or decreasing trend in the measured hardness values.
- When testing curved parts, it is extremely important that the part is properly aligned such that the indentation is made at the apex of a convex surface or at the bottom of a concave surface. The proper alignment of a V-shaped or

a double-roller style anvil may be checked by first making one Rockwell test on a cylindrical piece, then, after rotating the anvil 90 ° without moving the test piece, make a second test. If the second test falls exactly at the same location as the first test, the alignment of the indenter is likely satisfactory.

⃠ Testing Precaution

- The anvil must present the material test surface perpendicular to the indentation direction of the indenter. If the test surface is tested at an angle with respect to the indentation direction, the measurement will be adversely affected, usually lowering the measured value from the true hardness.

3.3.6 Hysteresis

Each time a Rockwell hardness test is made, the testing machine will undergo flexure in some of the machine components including the machine frame. If the flexure is not entirely elastic during the application and removal of the additional force, the testing machine may exhibit hysteresis in its flexure. Since the indenter-depth measurement systems of most Rockwell hardness machines are directly connected to the machine frame, any hysteresis would be reflected in the indenter-depth measurement system. A hysteresis effect can also occur in the indenter-depth measurement system itself as the direction of measurement reverses after applying the total force. In both cases, the hysteresis is likely to result in an offset or bias in the test result.

⃠ Testing Precautions

- Excessive hysteresis may indicate problems with the Rockwell machine caused by worn or dirty parts, such as in the depth measurement system, the elevating screw and anvil seat.

3.3.7 Repeatability

The repeatability of a hardness machine is its ability to obtain the same hardness measurement result on an ideally uniform material over a short period of time where the test conditions (including the operator) do not vary. Imagine a material that is perfectly uniform in hardness, which has been ideally prepared for Rockwell hardness testing. If a small number of Rockwell tests were made repeatedly on this material, it would be found that the measurement results were likely not identical, but rather they varied randomly over a range of values. The degree to which the measurement values agree provides an indication of the repeatability of the Rockwell hardness machine. As with most measuring devices, no matter how much effort is made to eliminate the sources of this random variability, it is impossible to do away with completely.

All Rockwell machines exhibit some level of lack of repeatability, which sporadically adds error to measurement values. Whereas, errors in force, depth, and hysteresis are typically systematic errors that contribute to a bias in the hardness measurement, lack of repeatability is a randomly occurring error. The lack of repeatability will typically increase in instances such as when parts of the hardness machine are worn, when excessive friction is occurring during a test, or when the machine requires cleaning. The level of repeatability of a hardness machine often varies between different Rockwell scales due to variances such as the force levels and types of indenters. The repeatability may also vary at different hardness levels within the same scale due to the variations related to differing indentation depths.

The ASTM(2) and ISO(4) standards specify a method for assessing the lack of repeatability of a Rockwell machine, which involves making hardness measurements across the surface of reference test blocks (see 5.2.1). The acceptability of the testing machine is determined from the difference between the maximum and minimum measured hardness values. Satisfactory tolerances on this measure of repeatability vary from 1.0 to 2.0 Rockwell units for ASTM and from 1.2 to 6.6 units for ISO, depending on the Rockwell scale and hardness level.

3.3.8 Indenters

The indenter is a major contributor to Rockwell hardness measurement error. Both the spheroconical diamond indenter and the ball indenter have characteristics that can cause significant measurement biases. In fact, indenter measurement bias has often been used to offset other measurement errors associated with the hardness machine. Like hardness machines, the measurement performance of a Rockwell indenter is dependent on more than its physical parameters. Differences in indenter performance may also be due to the indenter's manufacturing process. Two indenters with virtually the same shape may produce significantly differing hardness measurements. It is recommended that the indenters to be used be certified for performance with respect to a higher-level master indenter. In the past, an often-used procedure to certify Rockwell indenters was to make hardness tests on reference test blocks, and compare the measurement to the block value. When using this procedure, if the indenter performance did not agree with the block value, it was difficult to determine whether the source of the error was due to the indenter, the standardizing machine, the reference block values, or some combination of these variables.

The test method standards state acceptability tolerances for the performance of diamond indenters. ASTM(2) allows the performance to deviate from 0.5 to 1.0 Rockwell units from test block values, depending on the hardness level.

ISO[4] allows the performance to deviate 0.8 Rockwell units from the performance of a reference indenter. There are currently no requirements for the performance of ball indenters in either ASTM or ISO standards. It should be noted that a Rockwell indenter has formally been referred to as a "penetrator" or "stylus."

There are several different designs currently used for the base (opposite end of the indentation tip) of Rockwell indenters because of the varying styles of indenter holders found on different manufacturer's hardness machines. Indenters may be attached to machines using such methods as slip fittings, threaded fixtures, or with a collet fixture. Not all indenter designs can be used with all holder styles. Whatever method is used, it is imperative that there is no movement of the indenter in its holder during a test.

★ Good Practice Recommendations

- Indenters should be used that are certified to be within tolerances for both shape (geometry) and performance with respect to a reference indenter. This applies to all types of Rockwell indenters. In the past, it was common for diamond indenters to be certified for performance only.
- Only indenters should be used that have been verified for use with the particular Rockwell machine, such as during an indirect verification (see 5.2). In cases that other indenters must be used, they should be verified in some manner for use with the testing machine. The best verification method is to perform a full indirect verification of the applicable Rockwell scales using the indenter in question. Other verification techniques may also be appropriate.
- Periodically, indenters should be visually inspected for damage with the aid of adequate magnification (20X or higher).
- Every effort should be made to keep indenters clean, particularly the indenting portion and the surface that is seated against the testing machine. Indenters should be cleaned periodically in a manner that will not leave residue on the indenting portion of the tip.
- Each time an indenter is installed, regardless of its design, its seating surface must be adequately seated against the indenter holder by making repeated hardness tests on a uniform piece of material, such as a test block. Repeat the tests until there is no increasing or decreasing trend in the measured hardness values.

⃠ Testing Precaution

- If an indenter is dropped or hit with the test piece or anvil, it is imperative that before using it further, it should be thoroughly inspected for damage and verified for performance for each Rockwell scale that is used. Performance verification is necessary because the measuring ability of an indenter, particularly a diamond indenter, can change significantly without any outward visible signs of damage.

3.3.8.1 Spheroconical Diamond Indenter

The Rockwell diamond indenter is used with the HRA, HRC, HRD, HR15N, HR30N, and HR45N scales. The diamond indenter scales are typically used when testing harder materials such as steel, tungsten, and cemented carbides. Diamond is needed for testing hard materials to ensure that the indenter itself does not deform during the indentation process. Any permanent deformation of the indenter would adversely affect the hardness measurement of the test material. A typical Rockwell diamond indenter consists of a metal holder into which a diamond tip is permanently attached. The diamond tip is specified by test method standards to have a spheroconical geometry with a 120 ° included cone angle and a 0.2 mm radius tip, with the cone and radial tip blending in a tangential manner as illustrated in Figure 4.

There are several error sources that can affect the measurement performance of the Rockwell diamond indenter. Some error sources are obvious, and others are difficult to determine. The most common error source is an incorrectly shaped spheroconical diamond tip. In the past, this commonly occurred because diamond is very difficult to machine into the spheroconical geometry, and, until recently, many indenter manufacturers did not have adequate instruments to accurately measure the diamond shape. Common practice in the manufacture of diamond indenters was to machine the diamond shape close to nominal, and then certify the indenter only by performance testing with little or no actual direct verification of its geometry. Increasingly, today's manufacturers have developed the capabilities to accurately measure the indenter geometries and detect variations that are out of tolerance.

Form errors in the indenter shape often translate into significant errors in the hardness measurement. This is because a Rockwell hardness value is related to the volume of material displaced by the indenter during the application of the Rockwell test forces. The displaced volume is related to how deep the indenter penetrates the material. If two Rockwell tests are made using indenters having similar but slightly different geometries, essentially the same volume of material will be displaced, but the depth of indentation will vary, and, thus, the calculated Rockwell hardness value will be different.

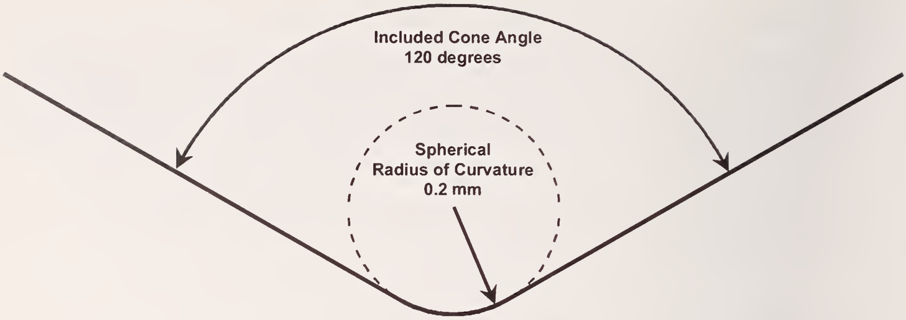


Figure 4.

Diagram of cross-sectional view of spheroconical diamond indenter tip.

If a series of Rockwell hardness tests is made on a number of materials ranging progressively from soft to hard, then as the material hardness increases, less of the diamond tip penetrates the material. Therefore, depending on the hardness of the test material, errors in the cone angle or tip radius will cause varying degrees of error in the hardness measurement. Because harder materials produce shallower penetration depths, the test material is primarily in contact with the radial tip, which will have the greater influence on measurement error. The cone angle will have a greater influence for softer materials exhibiting deeper indentations, since the test material is being displaced by more of the conical portion of the diamond.

Other sources of error include form error at the tangential blend, the surface roughness of the diamond, the alignment of the indenter axis with respect to the seating surface of the indenter to the test machine, a poorly machined seating surface, and hysteresis in the indenter itself as it is loaded and unloaded, possibly due to problems with the interface between the diamond and the metal portion of the indenter. Many of these indenter problems may produce measurement errors that will vary depending on the hardness scale used, the hardness level of the test material, or the type of test material. Consequently, Rockwell diamond indenters are sometimes certified for specific Rockwell scales.

★ Good Practice Recommendation

If possible, a diamond indenter should be chosen that is certified for each Rockwell scale that will be used or as many scales as possible. To obtain the highest accuracy, use of more than one diamond indenter may be desired, each certified for specific Rockwell scales. This allows an indenter to be chosen that may agree more closely with the performance of a reference indenter for a specific Rockwell scale, even though the performance is not as close (or possibly not acceptable) for other diamond scales. In the United States, Rockwell diamond indenters are sometimes designated as being a "C," "N," or "A" indenter. Usually, these designations mean the following: a "C" indenter is appropriate for use with the regular Rockwell scales (HRA, HRC, HRD), a "N" indenter is appropriate for the superficial Rockwell scales (HR15N, HR30N, HR45N), and an "A" indenter usually refers to being acceptable for testing carbides at the high end of the HRA scale. Be aware that the ISO test method requires that each diamond indenter be performance certified for all Rockwell scales requiring a diamond indenter.

3.3.8.2 Ball Indenters

Rockwell ball indenters are used with all Rockwell scales with the exception of the A, C, D, and N scales for which the diamond indenter is used. Typically, ball indenters are used when testing materials such as soft steels, copper alloys, aluminum alloys, and bearing metals. There are four standard sizes of ball indenters specified by ASTM[2] having diameters of 1.588 mm ($^1/_{16}$ in), 3.175 mm ($^1/_8$ in), 6.350 mm ($^1/_4$ in), and 12.70 mm ($^1/_2$ in). The ISO[4] specifies only the 1.588 mm ($^1/_{16}$ in) and 3.175 mm ($^1/_8$ in) diameter balls. The choice of indenter size, and, thus, hardness scale, is largely based on the hardness and thickness of the test material. Generally, the ball size is increased for thinner and softer materials. A typical Rockwell ball indenter consists of a metal holder for the ball with a threaded cap to hold the ball in place.

Rockwell indenter balls can be made of either steel or tungsten carbide (WC). In the past, most Rockwell hardness testing with ball indenters has used steel balls, typically bearing balls; however, there is currently a general move towards the use of tungsten carbide balls. Presently in the year 2000, ASTM specifies steel balls as the standard indenter, and, until recently, ISO had required that Rockwell tests be performed using only steel balls but now allows the use of tungsten carbide balls. A problem with steel balls is that they tend to flatten over time at the contact point with the test specimen, particularly when testing harder materials. An indenter with a flattened ball will not penetrate as deeply into test materials, indicating an apparent higher hardness for the material. The tungsten carbide ball was introduced to help overcome this problem. The harder tungsten carbide is much less susceptible to flattening than steel balls.

Tests have indicated[14] that the use of tungsten carbide ball indenters may result in a lower hardness measurement than when a steel ball indenter is used. This may be partly due to differences in the compliance of the two ball materials. Fortunately, the publishers of the ISO standard also require that the measurement values be reported with a scale designation ending in the letter "S" when a steel ball is used or "W" when a tungsten carbide ball is used.

Although this designation differentiates between tests made with the two indenters, users of the measurement data must be aware that measurement differences may occur.

★ Good Practice Recommendation

- When steel ball indenters are used, it is important that performance verification checks with reference test blocks be made frequently. This is because of the tendency of the steel ball to flatten over time, particularly when testing harder materials. Since the flattening may increase gradually, the performance of the indenter should be consistently monitored at a rate appropriate for the usage of the indenter and the hardness level of the material tested.

⃠ Testing Precaution

- A steel ball can be flattened quickly if a test is mistakenly made on a material above the appropriate hardness range (over 100 HRB) or if the indenter is hit by the anvil or is used to test too thin material.
- When testing very soft materials, it is important to ensure that the design of the indenter cap allows adequate protrusion of the ball. Otherwise, the cap may contact the test material, preventing full penetration into the test material, and result in an erroneously high hardness value. Be aware that it is possible for the cap to contact the test material without any physical indication on the surface of the test material.

3.4 Hardness Measurement

The Rockwell hardness test method procedure is described and specified by the test method standards. To facilitate comparisons with other Rockwell hardness data, the requirements of the standards should be adhered to. In cases where the measurement of hardness is to meet a product or material specification and must follow a particular test method standard document, the test procedures must adhere to the requirements of the standard.

3.4.1 Set Appropriate Rockwell Scale

The Rockwell machine must be set up for testing the chosen Rockwell scale, such that the appropriate indenter type and force levels are used. The appropriate indenter and force levels, corresponding to each Rockwell scale, are given in Figure 1 and by the test method standards.

★ Good Practice Recommendations

- The user should confirm that the indenter chosen for testing has been previously verified for use with the particular testing machine.
- Whenever the test forces, indenters or anvils are changed, a daily check or verification (see 6.2) of the performance of the testing machine should be performed using reference test blocks as described by the test method standards. In cases where the anvil to be used cannot be used for testing a test block (e.g., a V-anvil for testing round parts), then parts or test specimens of known hardness that can be tested with the anvil should be maintained by the user to perform the daily check. A daily verification should be performed at least once each day of testing regardless of whether the indenter, anvil, or forces are changed. The daily verification tests should be performed after the indenter and/or anvil have been seated.

⃠ Testing Precautions

- Some older designs of Rockwell machines that apply the total force by weights acting through a lever arm may require that the proper weights be added or removed from a hanger rod. Be aware that, in some cases, the weights have been calibrated for a specific hardness machine and may not produce the correct forces on other machines.
- Care must be taken to not contact the indenter when installing or removing an anvil. Many indenters are damaged in this way. If the anvil contacts the indenter, the indenter should be inspected and performance verified (see 6.2) prior to further testing.

3.4.2 Testing Cycle

The Rockwell testing cycle is the sequence of operations that the hardness machine undergoes during a measurement. The testing cycle includes the rates at which the forces are applied and the time periods that the forces are held constant, referred to as dwell times. The Rockwell hardness testing cycle can be separated into eight steps, as indicated in Figure 5. These steps fall into two categories: (1) application or removal of test forces; and (2) dwell times. Annex B provides expanded explanations of the individual effects that each of the testing cycle steps has on the hardness result.

When used to test most materials, particularly metals, the Rockwell hardness test is testing cycle dependent. By using different testing cycles, the measurement will yield different hardness results. Because the Rockwell test is testing cycle dependent, the hardness result is not complete unless the testing cycle that was used is also known. This dilemma of obtaining different

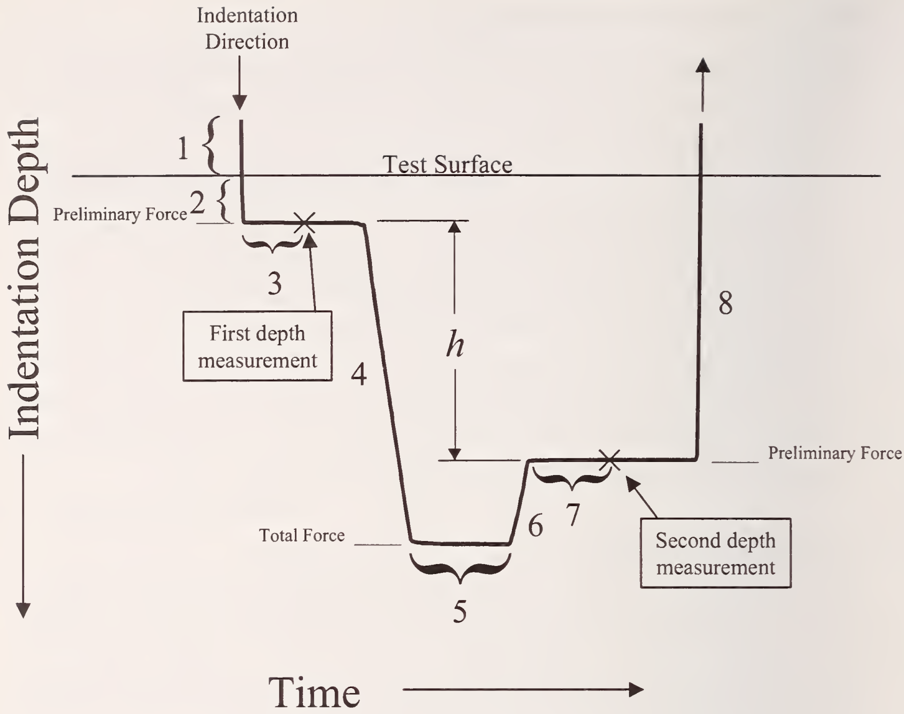


Figure 5.
Eight steps of the Rockwell test cycle.

hardness values for the same material is partially solved by adhering to test method standards, which define tolerances on the testing cycle.

3.4.2.1 Application or Removal of Test Forces

The step in the Rockwell testing cycle where the preliminary force is increased to the total force level (step 4 in Figure 5) has been shown[15] to significantly affect the measured hardness value. By changing the rate that the force is applied, particularly during the last part of the force application, a range of hardness values can be obtained. The effect may be due either to rate sensitivity of the material under test, or to the dynamics of the hardness tester, or a combination of both. The magnitude of the rate effect is highly dependent on the type and hardness of the test material. It is important that the test forces are applied at rates in accordance with the test method standards. In both the cases of too rapid loading or loading too slowly, the test measurement can be adversely affected.

3.4.2.2 *Dwell Times*

Each of the three dwell time steps of the testing cycle affect the hardness result because of creep or elastic recovery of the test material occurring during these periods of constant force. The effects of the dwell times can be summarized as:

1. Errors in the dwell time will produce the largest differences in hardness measurement results when shorter dwell times are used. The user should take this into account when choosing an appropriate test cycle. An increase in testing speed may reduce the repeatability in measurement results.

2. In general, the Rockwell hardness number is most affected by the total force dwell time, followed by the preliminary force dwell time, and then the recovery dwell time. This depends somewhat on the hardness level of the material.

★ Good Practice Recommendations

- When Rockwell hardness comparisons are to be made between two laboratories, or two test machines, or even between two tests made on the same hardness tester, the testing cycles that are used should agree as closely as possible, particularly when short dwell times are used. How close the test cycles should agree depends on the desired precision of the hardness result. For example, in situations where the Rockwell hardness measurement must only agree within several Rockwell hardness points, perhaps any testing cycle within the specified ranges would be acceptable. However, in cases where the results must have a close comparison, or there is disagreement between laboratories, each Rockwell measurement should be made using the same test cycle.

- When the testing machine design requires that the operator either fully or partially perform the test procedure manually, the operator should make every effort to operate the machine such that testing cycle requirements are being met.

⃠ Testing Precaution

- In cases where the operator applies the preliminary force manually, such as is common for older machines, the correct preliminary force level may be overshot. The operator must not adjust back to the proper force. The error to the measurement value has already occurred. In this situation, the test should be stopped and a different location tested.

3.4.3 Seating the Anvil and Indenter

Prior to making Rockwell measurements, the hardness machine anvil and indenter must be adequately seated. This may be accomplished by performing standard Rockwell hardness tests on a material having a uniform hardness, such as reference test blocks. The seating tests should be repeated until the successive measurement values show no trend of increasing or decreasing hardness.

3.4.4 Cleaning the Anvil and Indenter

The hardness machine anvil and indenter should be thoroughly cleaned per manufacturer's recommendations. In the absence of manufacturer's cleaning instructions, it is recommended that the anvil and indenter be cleaned with ethyl alcohol and dried using a lint free cloth. Lastly, blow the surfaces clean of dust using filtered air, such as from a commercial compressed air can or bottle. Do not blow clean by mouth.

3.4.5 Placement and Removal of Test Material

Usually, material to be tested with a Rockwell hardness machine is placed on the anvil by hand by the operator. In some cases, mechanical systems are used to automatically place and remove samples. The contact area of the test material and anvil must be clean without the presence of dust, dirt, or lubricant. It is extremely important that the test material be well supported to prevent any movement during the test.

★ Good Practice Recommendation

- When a spot anvil is used that is too small to support the test material without assistance by the operator, the operator should carefully place the test material onto the anvil so that it is flat against the anvil surface. The operator should hold the material steady during the application of the preliminary force, and release it just before the preliminary force is fully applied. This type of testing requires a skilled operator that can perform the test without applying any added force to the test from misalignment or movement of the test sample.

⃠ Testing Precautions

- Care must be taken to not contact the indenter when placing the test material on the support anvil and particularly when removing the test material. Many indenters are damaged in this way. If the test material contacts the indenter, the indenter should be inspected and performance verified (see 6.2) prior to further testing.

- The test material must be placed on the anvil such that the anvil is not scratched, indented, or damaged in any way.

3.4.6 Making the Measurement

As with most testing equipment and instrumentation, the operation of Rockwell hardness machines varies from manufacturer to manufacturer and from model to model. Depending on the machine model, the responsibility of the operator can vary from manually applying and controlling each of the test forces to simply pushing a button. The user should read and follow the recommended operating procedures found in the manufacturer's manual.

⃠ Testing Precautions

- The test material must not be held by hand during the testing process, except as allowed when using the spot anvil (see above). Holding the test material by hand can cause movement of the material during a test.
- During the testing process, the operator should avoid contact with the testing machine, the test material, and the table or stand supporting the testing machine, except when required to operate the machine. Contact can induce shock and vibration that can affect the test.
- When testing curved parts, special care is needed to ensure that the specimen support correctly aligns the part and prevents movement of the part during a test.

3.4.7 Spacing of Indentations

As a Rockwell hardness measurement is being made, the material deformation zone extends in all directions around the indentation. This process typically increases the hardness of the deformation zone by inducing residual stress and cold-working the deformed material. If a second indentation is made near an existing indentation such that the deformation zone surrounding the new indentation overlaps the hardened material surrounding the previous indentation, then the apparent measured hardness likely will be erroneously elevated. This effect is increased the closer two indentations are made to each other until the indentations become so close that the wall of the original indentation begins collapsing, likely lowering the apparent hardness.

The general rule as specified by the ASTM[2] test method standards is that the distance between the centers of two indentations must be at least 3 times the diameter of the indentation. The ISO test method standard[3] specify that the distance be at least 4 times the diameter of the indentation (but not less than 2 mm). Although these are reasonable guidelines, tests have shown[15] that interaction with an adjacent indent can occur at these and greater distances. Also, take into consideration that the effect will be multiplied by multiple adjacent indents. The user should determine the appropriate distance for the material to be tested.

3.4.8 Testing Curved Surfaces

Rockwell numbers obtained from measurements made on curved surfaces must be corrected depending on the radius of curvature and whether the surface is convex or concave. In the case of convex surfaces, such as the outside of a cylinder, a correction value must be added to the test result to increase the measured hardness value. This is because a convex surface curves away from the indenter tip providing less surrounding material to support the indenter than is the case for flat material. As a result, the indenter penetrates the material more deeply and indicates a lower hardness than the true value. Similarly, for concave surfaces, a correction value must be subtracted from the test result to decrease the apparent hardness value. This is because a concave surface curves towards the indenter tip, and provides additional material to support the indenter than when testing flat material, and, consequently, produces a shallower indentation and a higher hardness than the true value. As the radius of curvature gets smaller, the error in the measurement result becomes more pronounced requiring a larger correction to be made.

The ASTM[2] and ISO[4] standards specify values for correcting tests made on a few types of curved surfaces. The corrections given in test method standards are to be considered approximations only. Both ASTM and ISO give corrections for tests made on convex cylindrical surfaces. ISO also provides limited corrections for testing on convex spherical surfaces. These correction values are to be added to the measured hardness value to obtain an approximation of the actual hardness of the material. If correction values for concave surfaces are not available, the correction values given by the test method standards for convex surfaces may be subtracted from the measured value to provide a rough approximation of the material hardness. This procedure for correcting tests on concave surfaces should only be used to obtain an approximate value and not to meet a specification.

★ Good Practice Recommendation

- It is recommended that users develop their own correction values specific for the type of material and radius of curvature that will be tested. This may be done by testing samples of the same material in both the curved and flat geometries, for example, by testing the curved surface and flat ends of a cylinder. Be certain that the test surface conditions are the same for both the curved and flat specimens.

⃠ Testing Precautions

- When testing curved parts, it is extremely important that care be taken to ensure that the part is properly aligned such that the indentation is made at the apex of a convex surface or at the bottom of a concave surface (see 3.3.5). It is also extremely important to ensure that the part does not move during testing.
- When applying correction values provided in the test method standards for tests on curved surfaces, be certain that the corrections used are for the same geometry as the test piece. Be aware that tests on surfaces that curve in two axes, such as a sphere will require different corrections than surfaces that curve in only one axis such as a cylinder.
- Depending on the hardness level, Rockwell tests should not be made on curved surfaces below a certain radius of curvature due to the errors associated with the large corrections that would be needed. ASTM and ISO recommends that for Rockwell scales using a diamond indenter or a 1.588 mm ($^1/_{16}$ in) diameter ball indenter, regular Rockwell scale tests should not be made on convex cylinders below 6.4 mm ($^1/_4$ in) in diameter, and superficial Rockwell scale tests should not be made on convex cylinders below 3.2 mm ($^1/_8$ in) in diameter. ISO also states that Rockwell tests on the A, C, D, N, and T scales should not be made when the correction is greater than three Rockwell units, and tests on the B scale should not be made when the correction is greater than five Rockwell units.

3.4.9 Test Environment

The degree to which the testing environment affects the Rockwell hardness test is generally difficult to quantify; however, three of the major environmental factors that can contribute to measurement error are the testing temperature, excessive vibration and general cleanliness.

★ Good Practice Recommendation

When choosing the location for installing a hardness machine, consider the environmental conditions over the entire workday as well as seasonal changes throughout the year.

3.4.9.1 Temperature

The test temperature can affect Rockwell hardness measurement results due to two causes: (1) variations in the operation of the testing machine due to temperature; and (2) temperature dependency of the test material. Variations in the operation of the testing machine cannot be generalized for all Rockwell testing machines. Because of the many designs of Rockwell hardness machines having different principles of operation and instrumentation, it is likely that each will have unique dependencies on temperature.

The temperature dependency of the test material will vary depending on the type of material and the Rockwell scale that is used for testing. As an indication of the typical magnitude of this effect, the following relationships are provided. Yamamoto and Yano[(16)] determined that for their specific HRC test blocks, the temperature dependence was -0.03 HRC/°C at 20 HRC, -0.02 HRC/°C at 40 HRC and -0.01 HRC/°C at 60 HRC. W. Kersten[(16)] determined a similar relationship for the material he tested of -0.0185 HRC/°C, independent of HRC level.

★ Good Practice Recommendations

- Placement of a Rockwell hardness machine in an area that will have to operate over a wide range of temperatures should be avoided whenever possible. To obtain the most repeatable results, the temperature of the hardness machine and the test material should be maintained within a narrow temperature range. The appropriate range is dependent on the user's needs. The test method standards state typical testing temperatures within the range of 10 °C to 35 °C. The ISO test method standard requires that a test temperature of (23 ± 5) °C be used when tests are carried out under controlled conditions.
- For some industries, it is common for a Rockwell machine to be used in an environment that is subject to wide temperature fluctuations. In these cases, it is important to ensure that the Rockwell machine is capable of performing within tolerances over the range of temperatures. This may be determined by verifying the performance of the hardness machine with reference blocks as the temperature of the testing environment changes. When performing these verifications, it is desirable to separate any affect due to the temperature dependency of the reference block material. To the extent possible, prior to and during the verifications, the blocks should be maintained near to the temperature at which they were calibrated. However, condensation on the test block must be avoided.
- Although the hardness machine may operate satisfactorily over a wide temperature range, the test material may also exhibit varying hardness

values at differing temperatures. Consequently, when the temperature dependency of the test material is not known, it is recommended to report the test temperature with the hardness measurement results when the temperature is suspected to be a factor.

3.4.9.2 Vibration

The Rockwell test method standards warn the user to avoid making Rockwell hardness measurements when the testing machine is subjected to excessive vibration or shock. As with the other environmental factors, the degree to which vibration may affect the hardness measurement is dependent on the design of the testing machine.

★ Good Practice Recommendation

- Rockwell hardness machines should be placed on an isolated table or workbench, which is not shared with other equipment.
- Testing locations susceptible to excessive vibration should be avoided such as near machinery, near worker high traffic areas, on loading docks, or adjacent to heavily traveled roads or railroad tracks.

3.4.9.3 Cleanliness

Many designs of Rockwell hardness machines are highly susceptible to measurement errors when dust, dirt, or oil is deposited and accumulated on machine components. A more critical problem can occur when these types of contaminants adhere to the specimen support anvils, elevating screw, or, in particular, to the indenter.

3.4.10 Reporting Results

Rockwell hardness numbers should be reported as required by the test method standards using appropriate rounding techniques. The numeric value must be followed by the symbol HR and the scale designation. For example, 64 HRC represents a Rockwell hardness number of 64 on the Rockwell C scale, and 81 HR30N represents a Rockwell superficial hardness number of 81 on the Rockwell 30N scale. The ISO test method standards state the additional requirement that when a ball indenter is used, the scale designation is followed by the letter “S” when using a steel ball and the letter “W” to indicate the use of a tungsten carbide ball. For example, 72 HRBW represents a Rockwell hardness number of 72 on the B scale measured using a tungsten carbide ball indenter.

3.4.11 Conversion to Other Hardness Scales or Properties

There is no general method of accurately converting the Rockwell hardness numbers determined on one scale to Rockwell hardness numbers on another scale, or to other types of hardness numbers, or to tensile strength values. Nevertheless, hardness conversion tables are published by ASTM[17], in the literature, and often by hardness equipment manufacturers. Such conversions are, at best, approximations and, therefore, should be avoided except for special cases where a reliable basis for the approximate conversion has been obtained by comparison tests.

4 REFERENCE TEST BLOCK STANDARDS

Rockwell hardness test blocks are reference standards for transferring Rockwell hardness scale values from one standardizing level to a lower level; for example, transferring national hardness scale values directly to secondary standardizing laboratories, or transferring the national hardness scale values to industry through the secondary standardizing level. Rockwell hardness test blocks are also used for verifying or comparing the performance of Rockwell hardness machines and indenters. The test method standards specify requirements for the preparation, size, finish, uniformity, and standardization of reference test blocks.

Historically, Rockwell test blocks are standardized (also referred to as calibrated) to determine the average hardness of the test surface of the block. Normally, the calibration laboratory accomplishes this by making a number of measurements across the block surface and then calculating the average of the measurements. This is the usual standardization process whether the blocks are standardized by the primary national metrology institute level or by secondary commercial laboratories.

Because no materials are perfectly uniform in hardness, all reference test blocks will have some hardness variation across the test surface. In most cases, the hardness varies smoothly across the surface, but the variation is different from block to block. The hardness variation is primarily due to the test block manufacturing process. Figure 6 illustrates examples of the hardness variation in four 25 HRC level test blocks.

The certified hardness value provided with a test block is an estimation of the average hardness of the entire test surface; however, the hardness at individual test locations will vary within a range of values extending both above and below the certified average hardness value. This variation in hardness across the surface is referred to as the non-uniformity of the test block. The test method standards specify tolerances on the degree of acceptable non-uniformity, which varies depending on Rockwell scale and hardness level.

4.1 Primary Reference Test Blocks

Primary reference test blocks are standardized using primary standardizing machines in accordance with the hardness definition. Usually, the National Metrology Institute (NMI) of a country standardizes the primary reference test blocks and maintains the national hardness scales. The National Metrology Institute in the United States for Rockwell hardness is NIST.

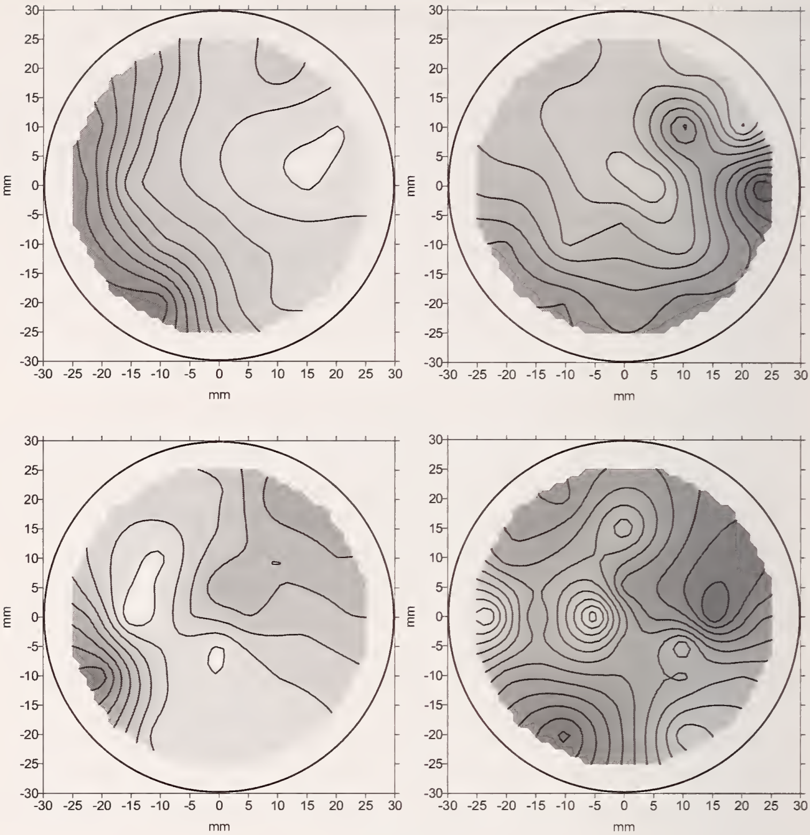


Figure 6.

Four examples of the hardness profile across the test surface of 25 HRC test blocks, illustrating how the non-uniformity in hardness can vary within a block and differs from block to block. Each line represents a hardness change of 0.02 HRC. Light to dark areas represent hard to soft areas.

4.1.1 NIST SRMs for the Rockwell C Scale

Each Rockwell hardness scale covers a range of hardness levels. To transfer the U.S. national HRC scale values to industry requires more than one transfer standard for the entire scale. However, production of hardness blocks at all levels of HRC hardness is not feasible for NIST. It was determined that industry needs test blocks at the levels specified in test method standards for the calibration and verification of Rockwell hardness testing machines. For the HRC scale, ASTM and ISO specify three ranges of hardness. The NIST reference test blocks for the HRC scale reflect these ranges and are certified at three hardness levels: 25 HRC, 45 HRC, and 63 HRC, which are available for purchase as a Standard Reference Material (SRM® 2810, 2811, and 2812, respectively)[18].

Currently, NIST offers Rockwell hardness test blocks for only the Rockwell C scale. Because the NIST SRMs are primary transfer standards, greater care in the usage of the test blocks is recommended than for commercial test blocks that are standardized by secondary calibration laboratories. Annex C provides recommended procedures for the use of NIST Rockwell hardness test block SRMs. These recommended procedures may be used as well when using secondary standards to help improve measurement accuracy.

As a consequence of the variation in hardness across a test block, NIST determines and provides the customer with two types of hardness certifications with each reference test block: (1) the certified average HRC hardness across the test surface of the block; and (2) certified HRC hardness values at specific untested locations on the test surface[(19)]. These two types of certifications characterize the hardness of the test block in distinctly different ways.

4.1.1.1 Certification of the Average Surface Hardness

As discussed previously, the certified average hardness value of reference test blocks is usually determined by calculating the simple average of several hardness measurement values taken across the surface of the block. The certification of the NIST SRM test blocks was partly based on the calibration measurements; however, it was also based on a NIST derived function that models how the hardness varies across the surface of the test block material. In the case of the NIST blocks, the certified average hardness value is the average of the hardness values predicted by the hardness function for all test surface locations, and not simply the arithmetical average of the seven NIST measurements. However, because the locations chosen for the seven NIST measurements provide a good representation of the range in surface hardness, the two averages are nearly identical in value.

4.1.1.2 Certification of Hardness at Untested Locations

A hardness measurement is destructive in that a specific location on a hardness block can be measured only once. For the second type of certification, certified HRC hardness values and the associated uncertainties are provided for specific untested locations on the test surface of the reference block, as illustrated by the open circles in Figure 7. Because hardness blocks are not uniform, NIST can only predict the hardness at these untested locations. The HRC hardness values were calculated using the surface hardness function. Using this formula, predicted hardness values may be calculated for any single untested location or for the average of two or more locations. For the NIST SRMs, however, certified values of only eleven locations are provided with the SRM test block. Section C.2 of Annex C provides the formulas used by NIST and gives examples of how to use these formulas.

Figure 7.

Hardness profile across the test surface of a NIST test block. The NIST calibration measurements are indicated by the solid circles, and the locations of the certified values for untested locations are indicated by the open circles.

This second type of NIST hardness certification provides the customer with a valuable tool for improving the hardness comparison measurements by reducing the influence of the test block non-uniformity. For example, the user can combine the seven NIST calibration measurements with the eleven predicted values to produce a profile map approximating the block surface hardness, and then, correct measurements depending on the test location on the block. The customer can also calculate better corrections by calculating hardness values using the same formula NIST used to determine the hardness at the eleven untested locations, as described in Annex C.

4.2 Secondary Reference Test Blocks

In the United States, and other countries throughout the world, the National Metrology Institutes are usually not the sole supplier of the needed reference standards for that country. Normally, secondary calibration laboratories produce and calibrate the majority of test blocks for use by industry. Whereas, NIST is planning to only provide test blocks for three hardness levels of each Rockwell scale, the secondary calibration laboratories usually provide reference blocks at multiple hardness levels, allowing a better verification for a specific level of hardness.

The secondary calibration laboratories are linked to the national Rockwell scales through the use of primary reference standards to calibrate their standardizing machines and, often, through some form of accuracy assurance program in connection with the primary standardization laboratory (NMI). In the United States, this is accomplished through direct verification of the secondary laboratories' standardizing machines using NIST traceable instruments and artifacts, indirect verification of the secondary laboratories' standardizing machines using NIST SRM test block standards, and voluntary participation in a calibration laboratory accreditation program. Because NIST SRMs are currently available only for the Rockwell C scale, the secondary reference test blocks of other Rockwell scales cannot be calibrated traceable to NIST Rockwell scales.

4.3 Use of Reference Test Block Standards

Rockwell hardness reference test blocks are used primarily for the indirect verification (see 5.2) and daily verification (see 6.2) of a Rockwell hardness machine. Reference test blocks are also useful when comparing the relative performance between two hardness machines by measuring the same blocks on both machines or for comparing the performance of two indenters. Proper care in the handling and use of reference test blocks is important to obtaining accurate measurements. It is critical that the reference test blocks not influence the hardness measurements due to improper use. The general procedure for testing reference test blocks is the same as the hardness measurement procedures discussed in 3.4. The following are additional recommended practices for the proper use of reference test blocks.

★ Good Practice Recommendations

- *Test temperature*: As discussed previously, the test temperature can affect Rockwell hardness measurement results due to the temperature dependency of the material being tested. When using reference test blocks, it is desirable to separate any effect due to the temperature dependency of the block material. To the extent possible, prior to and during the verifications, the reference test blocks should be maintained near to the temperature at which they were calibrated.

- *Anvil*: When reference test blocks are being used for the verification of a hardness machine, the same anvil must be used for the verification (when possible) as will be used for normal testing following the verification. In circumstances where the normally used anvil cannot be used for testing test blocks, an initial verification of the machine should be made using an anvil appropriate for testing reference test blocks. This anvil should then be replaced with the anvil normally used for testing, and a second verification should be performed. The second verification should be made on a typical part of known hardness that is normally tested with the anvil or some other appropriate test piece for which the correct hardness is known.

- *Inspection*: The bottom surface of reference test blocks should be visually inspected prior to use. The slightest dent, scratch, or spot of corrosion can significantly affect the measurement result. Attempts to repair mechanical damage on the bottom surface of test blocks should be avoided.

- *Cleaning*: Prior to use, it is recommended that the reference test block be cleaned. A recommended method for cleaning is to gently wipe the top and bottom test block surfaces with clean cotton or a cloth, thoroughly wetted with ethyl alcohol. The metal surfaces should immediately be dried using a soft lint free cloth or paper towel before the alcohol evaporates in the air. This cleaning must be performed in a manner that prevents a residue from remaining on the top or bottom surfaces. The cleaning should be followed by blowing the surfaces clean of dust using filtered air. The top and bottom surfaces should not be touched after cleaning.

- *Placement on the anvil*: Immediately before placing the reference test block on the hardness machine anvil, the top surface of the anvil and the bottom surface of the test block should be blown free of dust as before. The reference test block should be gently and carefully placed on the anvil before dust can return. The top test surface of the reference block should be blown free of dust prior to testing and occasionally during the period of use. When a flat anvil is used, the reference test block should be slid several times back and forth over the surface of the anvil to help seat the block on the anvil. Anytime the reference test block is lifted from and replaced on the anvil, the procedure described above in this paragraph should be repeated. When a spot anvil is used, extreme care should be practiced to ensure that the test block is supported parallel to the anvil surface until the indenter contacts the block, and the preliminary force is applied.

- *Preliminary indentation*: When a flat anvil is used, it is recommended that at least one preliminary Rockwell test be performed at any location on the test surface of the reference test block. The preliminary test will help seat the test block on the anvil. The measured hardness value of the preliminary test should be ignored. The user is cautioned not to make the preliminary indentation such that it contacts a previous indentation. Doing so may damage the indenter. A preliminary indentation is not necessary when using a spot anvil.

- *Testing cycle*: Reference test blocks are typically calibrated by performing Rockwell tests using a specific testing cycle. When reference test blocks are used for the verification of a hardness machine, a testing cycle should be used that replicates, as closely as possible, the testing cycle used by the standardizing agency when the block was calibrated. Deviations in the testing cycle dwell times or force application rate may result in measured hardness values that are shifted from measurements made using the standardizing testing cycle. Frequently, the testing cycle is not reported by the standardizing agency. In this case, a testing cycle should be chosen that is within the stated tolerances of the test method standards.

- *Measurement locations*: The locations for making measurements on reference test blocks should be as specified, or recommended by the test method standards, keeping in mind proper indentation spacing. Indentations should be randomly distributed over the surface of the test block when determining the measurement performance of the testing machine with respect to the certified average hardness value of the test block. Never fill the test surface with indentations by starting at one side of the block and progressively moving to the other side of the block.
- *Storage*: It is recommended that reference test blocks be stored in an environment that protects the blocks from mechanical damage, excessive oxidation and corrosion. Wrapping a test block in anti-corrosion paper is a good method for protecting the test block surface from corrosion and oxidation when not being used. Anti-corrosion paper for ferrous and nonferrous metals is commercially available. Although a coating of oil can protect a block surface, it is not recommended since the oil must be completely removed prior to testing the block. Test blocks should not be subjected to wide variations in temperature. Elevated temperatures should be avoided; particularly in the case of brass test blocks, which in some cases can age-harden the block changing its overall hardness.

⃠ Testing Precautions

- The certified hardness value provided with a reference test block is applicable only to the top test surface of the block. It does not represent the hardness of the bottom or edge surfaces of the test block, nor the material inside the test block. As such, NEVER make indentations on the bottom surface of a test block. Not only will the measurement values obtained be invalid for comparing with the block's certified hardness value for verification purposes, but also the reference test block can no longer be reliably tested on the top test surface. An indentation on the bottom surface will significantly affect subsequent hardness measurements. Any reference test block tested on the bottom surface must never be used for verification purposes and should be discarded.
- Once the test surface of a reference test block is filled, it should not be machined to remove the indentations for additional testing. As stated above, the hardness of the sub-surface material may differ from the hardness of the original test surface. Additionally, a Rockwell indentation deforms material well below an indentation making it difficult to determine when sufficient affected material has been removed from the block.

5 VERIFICATIONS OF ROCKWELL HARDNESS MACHINES

In order to reduce the overall error in a Rockwell hardness measurement, it is important that the different sources of error are identified and the significant error sources be reduced if possible. This can only be accomplished by assessing the separate parameters of the Rockwell test and verifying whether each is within acceptable limits. The test method standards specify two categories of methods that can be used to assess many of the aspects of the test. They are: *direct verification* and *indirect verification* of the hardness machine. Direct verification is a process for verifying that critical components of the hardness machine are within allowable tolerances by directly measuring such parameters as the test forces, depth measuring system, and machine hysteresis. Indirect verification is a process for verifying the measurement performance of the hardness machine by performing Rockwell hardness tests using standardized reference blocks and indenters.

★ Good Practice Recommendations

- Although ASTM and ISO test method standards presently do not require periodic direct verification of Rockwell machines, it is recommended that both direct and indirect verifications be performed periodically based on the usage and condition of the individual machine.
- When a testing machine fails to pass indirect verification of one or more Rockwell scales, direct verification should be used as a tool to determine the source of the problem rather than making blind adjustments of a machine component or electronic offsets to correct errors.
- When a testing machine fails to pass direct verification of one or more of its components, and cannot be brought within tolerances, it should be repaired or replaced.

5.1 Direct Verification

Periodic direct verification of the individual components of a Rockwell hardness machine is an excellent tool for determining what errors exist in the measurement system and for indicating that a problem may be surfacing. Unfortunately, direct verification is rarely done in practice; instead industry primarily relies on indirect verification to assess the measurement capability of Rockwell hardness machines. This is probably due to the difficulty and cost of performing direct verifications, and the fact that ASTM and ISO currently only require a limited direct verification of the hardness machine when the machine is new or installed.

5.1.1 Applied Forces Verification

The forces applied by the Rockwell machine should be verified periodically in accordance with the test method standards and using instrumentation having the appropriate accuracy, uncertainty, and traceability to national standards. The forces should be verified as they are applied during a Rockwell test; however, longer dwell times are recommended to acquire a stable measurement.

★ Good Practice Recommendation

For hardness machines that have the capability of adjusting the applied force levels, the forces should be adjusted as closely as possible to the center of the tolerances. Some Rockwell hardness machines allow the applied forces to be mechanically adjusted by the operator. Following direct verification and adjustment, further adjustment of the forces by the operator should not be allowed without subsequent direct verification of the adjusted force. Otherwise, the forces can easily be adjusted out of tolerance to offset other hardness machine problems that could have developed.

5.1.2 Depth Measuring System Verification

Direct verification of the depth measurement system should be accomplished as outlined by the test method standards using instrumentation having the appropriate accuracy, uncertainty and traceability to national standards. The verification should be performed in an appropriate manner that will verify the entire working range of the measurement device.

★ Good Practice Recommendation

- Some Rockwell machines are capable of electronically adjusting (or correcting) the depth measurement system, or the system for displaying the hardness value, based on comparisons with reference blocks. If such adjustments or corrections have been made, they should be reset or removed prior to verifying the indentation depth measuring system. Otherwise, the verification could indicate compliance for a system that is in fact out of tolerance.

5.1.3 Hysteresis Verification

A verification of the Rockwell machine should be made to determine the magnitude of any hysteresis in the flexure and measurement systems of the machine as a test is made. The goal of the hysteresis verification is to perform a purely elastic test that results in no permanent indentation. In this way, the level of hysteresis can be determined. The recommended method for assessing the level of hysteresis is to perform repeated Rockwell tests with a blunt indenter (or the indenter holder surface) acting directly onto a very hard test piece. The tests should be conducted using the highest test force that is used during normal testing. The hysteresis test is a somewhat difficult test to carry out. The slightest inelastic deformation at the interface of the blunt indenter (or holder) and the hard test piece will act to increase the apparent hysteresis. Every effort should be made to reduce any inelastic deformation.

If there were no hysteresis in a Rockwell machine, the measurements would indicate a hardness number of 130 Rockwell units when Rockwell ball scales B, E, F, G, H, and K are used and a hardness number of 100 Rockwell units when any other Rockwell scale is used. Currently, assessing the level of hysteresis in the testing machine is not required by ASTM standards. The ISO standards specify a test to evaluate the testing machine hysteresis allowing a hysteresis value of 0.5 Rockwell units for machines that have a clamping fixture for locking the test sample against the upper part of the machine frame and 1.5 Rockwell units for machines without a locking mechanism. Allowing a hysteresis level of 1.5 Rockwell units is excessive. Hysteresis should be limited to less than 0.5 Rockwell units for all machines.

★ Good Practice Recommendations

- When performing the hysteresis verification tests, it is important to choose an appropriate type of material that the blunt indenter or indenter holder will act against. The material should have the lowest ductility possible; yet have sufficient strength to support the test force. Metal carbides, hard ceramics, and thick glass have been used successfully for this purpose. Some hard metal test blocks when used for this purpose have exhibited a small amount of plasticity, which adds to the level of hysteresis, and, thus, are not recommended. Also, the test should be repeated in the same location many times before the first measurement is taken. Be aware that this test does not account for a possible hysteresis effect that could occur as a result of a problem at the interface of the indenter and the indenter holder, or any hysteresis due to the Rockwell indenter itself.
- For Rockwell machines that are capable of electronically adjusting (or correcting) the depth measurement system, any adjustments or corrections should be reset or removed prior to verifying the machine hysteresis. Otherwise, corrections can increase or decrease the indicated level of machine hysteresis providing an inaccurate estimate of the true hysteresis level.

5.2 Indirect Verification

Indirect verification, as specified by the test standards, involves assessing two aspects of the hardness machine: (1) its repeatability, or how well the hardness machine can repeatedly measure the same value on uniform material; and (2) its error (or bias), or how well the machine's measurement agrees with reference standards. The methods specified by the ASTM and ISO standards for assessing these parameters involve making hardness measurements distributed across the surface of reference blocks. Each Rockwell scale is evaluated in this manner usually by testing three reference blocks per scale; the hardness levels of the three blocks are chosen to cover the hardness range of each scale. It is important that the verifications of the hardness machine be made with the indenter that will be used for routine testing.

The assessment of both the repeatability and error are usually based on the same set of hardness measurements (typically five per reference block). The range of the measured values (maximum minus minimum) of each block provides an indication of the repeatability of the hardness machine when testing that specific hardness level. The difference between the average of the measured values and the certified average values of the respective reference block provides an estimation of the measurement error or bias.

5.2.1 Measurement Repeatability

When the repeatability measurements are based on tests made across the surface of a test block, the repeatability value will include an error contribution due to the non-uniformity of the test block. Depending on the degree of the hardness non-uniformity of the block, this error contribution can be significant. When performing an indirect verification, it is best to use reference test blocks having the highest degree of uniformity as possible.

★ Good Practice Recommendations

- The repeatability of the hardness machine should be assessed periodically and tracked over time. An increase in the lack of repeatability may indicate a problem with the Rockwell machine such as worn parts or the need for cleaning and maintenance.
- A better estimate of repeatability than suggested by the test method standards may be obtained by making a set of measurements in close proximity to each other, adhering to indentation spacing restrictions (see 3.4.7) such that there is no influence from a previous indentation. A pattern such as illustrated in Figure 8 is recommended. The close proximity of the measurements will reduce the effect of hardness nonuniformity in the test block. This procedure must not be used for assessing the measurement error as described below.

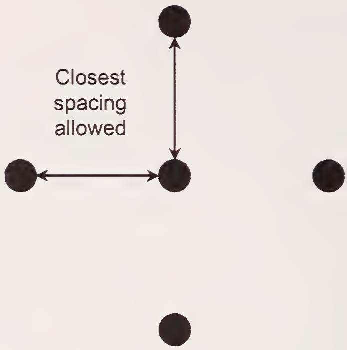


Figure 8.

Alternate pattern for repeatability measurements.

5.2.2 Measurement Bias or Error

The indirect verification of the measurement error or bias is the final indication of how all the errors in the test machine have combined together to influence the Rockwell hardness measurement. Even when all the parameters of a Rockwell testing machine are within specified tolerances, the final measurement result can be outside the allowable limits for the total error. This is because the errors associated with the separate Rockwell hardness test parameters each have acceptability limits that are relatively wide. If one were to combine all of the maximum allowable errors for the individual parameters, the combination would far exceed the specified allowable total error in measurement capability. Therefore, either the errors associated with the individual parameters must be reduced to as small a level as possible so that the combination of the individual errors does not exceed the total error tolerance, or the individual parameters must be adjusted within tolerances to produce offsetting errors so that when combined, the total error tolerance is not exceeded. Both of these techniques rely on direct verification of the adjustments.

Today, the most commonly used technique for handling measurement errors is to make an adjustment to one or more machine components to reduce the total measurement error. Unfortunately, since direct verification is rarely performed, it is not known whether it is the problem component that is being adjusted to reduce its error, or a within tolerance component that is being adjusted, possibly out of tolerance, to offset the error. It is generally felt by some hardness equipment manufacturers that, in the United States, a majority of Rockwell hardness machines would not pass a full direct verification due to individual parameters being out of tolerance and the associated error being offset by adjustments of other parameters. This practice is not recommended, and it can lead to problems when testing materials at hardness levels other than the test blocks levels used for the indirect verification or when testing materials other than the test block material.

★ Good Practice Recommendation

It is recommended that the as-found condition of the testing machine be assessed as part of an indirect verification. This is important for documenting the historical performance of the machine. This procedure should be made prior to any cleaning, maintenance, adjustments, or repairs. The as-found condition of the testing machine should be determined with the user's indenter(s) that are normally used with the testing machine. One or more standardized test blocks in the range of normal testing should be tested for each Rockwell scale that will subsequently undergo indirect verification. If the as-found condition verifications fall outside specified tolerances, it is an indication that hardness tests made since the last indirect verification may be suspect.

5.3 Correcting Measurement Biases

For Rockwell hardness machines that have successfully passed both direct and indirect verifications, there will continue to be some level of measurement error or bias with respect to the reference standards. If this bias is felt to be significant for the user's application, then it may be advantageous to make mathematical corrections based on the certified values of the reference test blocks. Presently, ASTM and ISO test methods do not address making mathematical corrections, although, in practice, a form of mathematical correction is commonly made for newer Rockwell machines capable of being electronically calibrated. These machines can determine correction curves by comparing certified test block values with values measured during an indirect verification. The curves are electronically stored in the Rockwell machine and correct future measurement values based on this curve. In general, mathematical corrections should only be made in cases where the Rockwell machine has been successfully verified.

A practical method for applying corrections for the measurement biases is to determine a linear calibration curve for the entire hardness scale. The linear calibration curve provides a correction value to be applied to future hardness measurements at any hardness level of that scale. The correction value is dependent on the Rockwell scale and hardness level of the material under test. A linear correction curve is chosen because indirect verifications are usually made with test blocks at only three levels of hardness for each Rockwell scale.

A curvilinear fit to only three data points often can produce impractical results at hardness levels other than the three verified levels. A separate and distinct correction curve is required for each Rockwell scale.

Figure 9 graphically illustrates how the biases can be corrected for a single Rockwell scale. The left axis represents the difference between testing machine measurements made on reference test block standards and the certified values of the reference test blocks. This is the error or bias determined as part of an indirect verification (average of machine measurements minus certified reference value). The bottom axis represents the hardness level that is measured. In this example, the round points indicate the bias values determined by testing three reference test block standards. A linear fit is made to the three bias values. The correction to be applied to future measurements is determined from the value at each point along the linear fit line. For example, when a future measurement is made at 25 HRC, the correction would be to add approximately 0.25 HRC to the measured value. The square data points and dashed line illustrate the result of applying these corrections to the bias values.

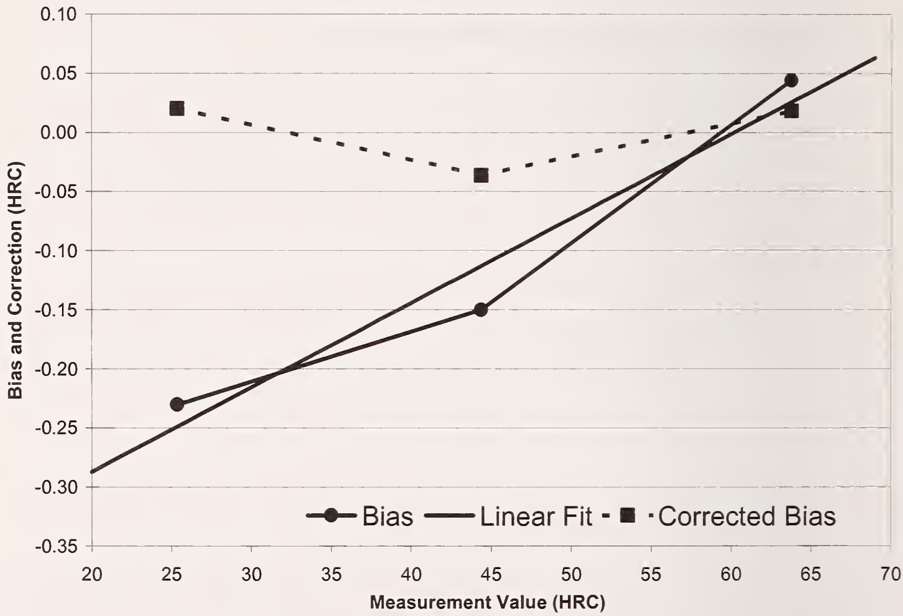


Figure 9.

Illustration of the three bias points corrected by a linear fit correction curve.

6 MONITORING TEST MACHINE PERFORMANCE

6.1 Reproducibility

In the previous discussion of the repeatability of a hardness machine in 5.2.1, it was imagined that a small number of Rockwell measurements were made on a perfectly uniform sample of material. Now, consider that the small set of Rockwell hardness measurements were reproduced at some periodic interval, for example once a day over an extended period of time always using the same test block and indenter. As before, each set of measurements would again vary within a fairly consistent range. In addition to this within-set variation, it also would be found that the average for each day's measurements would vary from day-to-day, as illustrated in Figure 10. This day-to-day variation is known as the level of reproducibility of the hardness machine. The variation is principally due to time dependent sources such as a change of operator or environmental factors.

The user should monitor the performance of the hardness machine over an extended period of time to assess the acceptable level of reproducibility. Subsequent monitoring can provide an indication that the Rockwell machine may be in need of maintenance or is being operated incorrectly. It is

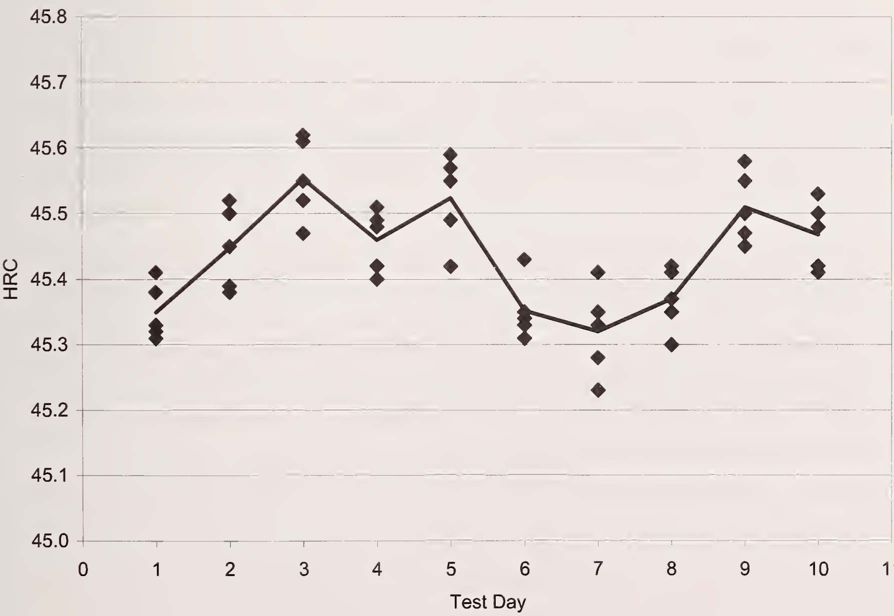


Figure 10.

Illustration of reproducibility data taken over ten days.

recommended that control charts, or other comparable methods, be used to monitor the performance of the hardness machine between verifications. Control charts provide a method for detecting lack of statistical control. Control chart data should be interpreted by the user based on past experience. The need for corrective action does not depend solely on data falling outside the control limits but also on the prior data leading to this occurrence. As a general rule, however, once the hardness machine is determined to be in control, a single occurrence of data falling outside the control limits should alert the user to a possible problem.

6.2 Daily Verification

The test method standards state procedures for conducting a daily verification of the Rockwell hardness machine. The intent of the daily verification is for the user to monitor the reproducibility of the hardness machine between indirect verifications. At a minimum, the daily verification should be performed each day that hardness tests are to be made for each Rockwell scale that will be used. It is recommended that the daily verification procedures be performed whenever the indenter, anvil, or test force is changed to ensure that these changes to the machine have not added error to the measurement due to occurrences such as erroneous adjustments, misalignment, or poor condition or cleanliness of the machine components.

★ Good Practice Recommendations

- Before performing the daily verification tests, ensure that the testing machine is working freely and that the indenter and anvil are seated adequately. The indenter to be used for the daily verification must be the indenter that will be used for testing.
- Whenever a Rockwell hardness machine fails a daily verification, the hardness tests made since the last valid daily verification may be suspect.
- It is highly recommended that the results obtained from the daily verification testing be recorded using accepted statistical process control techniques, such as control charts. This type of monitoring can alert the user to impending problems before the measuring capability of the hardness machine becomes unacceptable.

7 REDUCING MEASUREMENT DIFFERENCES AND ERRORS

Consider two Rockwell hardness machines, perhaps a supplier's machine and a customer's machine. Suppose both machines pass indirect verifications. Will the two machines then measure the same hardness value for a sample of material? In practice, there is a good chance there will be a measurable difference in hardness values. It is even possible there could be a significant difference, with one machine indicating that the material is within specification tolerances and the second machine indicating the material to be out of tolerances. Valid determinations of each machine's measurement uncertainty (see 8.3) should account for this discrepancy. The simple problem may be that the uncertainties of the measurements are too large to make valid comparisons. In this section, recommendations will be made for reducing these types of measurement differences.

7.1 Reduce Machine Component Operating Errors

It is generally not possible to make good Rockwell hardness measurements with a poorly operating machine. The initial consideration should be to use a Rockwell machine capable of measuring to the required accuracy and repeatability. As discussed previously, the errors in the operating components of the hardness machine should be identified and assessed through the direct verification process (see 5.1). Depending on the required level of accuracy, simply meeting the specified operating tolerances may not be adequate. Adjustments may be needed to bring each component to the center of tolerance. Unfortunately, for many types of Rockwell hardness machines, these types of adjustments are not possible in the field and, in many cases, may not be possible at all.

It is also important to use indenters that have been certified as meeting all of the requirements specified in the test method standards, including the shape and alignment. Until recently, obtaining certifications of the physical dimensions of diamond or ball indenters has been difficult. Once in use, indenters should be inspected frequently by visual means to help determine if damage has occurred.

7.2 Verify Machine Measurement Performance

The hardness measurement performance of a Rockwell machine does not depend solely on the parameters assessed during a direct verification. Once the components of the Rockwell hardness machine and indenter are considered to be operating within acceptable limits, its overall measurement performance must also be verified. This is accomplished by periodic indirect verification, coupled with daily verifications. It is important that the verifications of the hardness machine be made together with the indenter that will be used for routine testing.

7.2.1 Verification Frequency

The test method standards specify the maximum time allowed between indirect verifications of Rockwell machines as well as between daily verifications. These time intervals may not be adequate. More frequent verifications may be necessary depending on the condition of the machine, the level of machine usage, and the required measurement accuracy. As discussed in section 6, the verification results should be monitored and tracked to alert the user to a drift or erratic behavior in the machine's performance. These types of problems may be an indication of an escalating mechanical problem.

7.2.2 Uncertainty in the Certified Hardness Values of Reference Test Blocks

When a high level of measurement accuracy is important, performance verifications should be made using reference test block standards having as low an uncertainty as is practical. This applies in the cases of both indirect and daily verifications. The uncertainty in the certified values of the reference standards used for machine verifications will contribute to the overall measurement uncertainty of the hardness machine.

It is also important to consider to what standard the certified value of the reference test block is traceable. For example, an indirect verification, or daily verifications made with reference standards traceable to NIST standards, may not be appropriate when testing materials that must meet the national standards of another country or a company's own internal standards. This will continue to be an issue until international harmonization of the Rockwell scales is achieved.

Even when reference standards having the lowest available uncertainty are used for machine verifications, it may not provide sufficient measurement agreement in cases where a very high level of agreement is needed between two Rockwell machines. Bear in mind that machine performance verifications are normally considered acceptable when the measurement bias or error falls within tolerance limits. The combined levels of bias of the two machines coupled with the uncertainty of the certified values of the two test blocks may exceed the level of measurement agreement that is required. This measurement difference can be reduced, to a degree, by "correcting" future measurements of each hardness machine based on the biases determined from the respective machine verifications. The measurement difference can be further reduced by performing verifications of both machines using the same test blocks, and then, determine corrections based on the total measurement difference. When making any corrections of hardness measurements, the discussions in 5.3 should be considered.

7.3 Measurement Locations

The characteristics of the material to be tested must be taken into consideration when choosing appropriate measurement locations. Consider two hypothetical Rockwell hardness machines that agree perfectly in their measurement performance. Will the two machines then measure the same hardness value for a sample of material? The initial response would be yes; however, if the hardness of the material sample varies significantly from location to location, it would be possible to obtain significant measurement differences if the measurements were made at two different locations. Therefore, when a high level of accuracy in measurement comparisons is important, the same measurement locations should be tested. One solution is to make all measurements of both machines in one test area; however, the hardness result may not be representative of the entire sample of material. A better solution is to choose several test locations over the entire surface of the material to be tested by both machines. Each machine should make measurements at each of these locations adjacent to the measurements of the other machine. The measurement average of each machine could then be reasonably compared and would also provide a more valid estimate of the overall average hardness of the sample material.

8 TRACEABILITY, ERROR, AND UNCERTAINTY

8.1 Traceability

Traceability is defined by the International Vocabulary of Basic and General Terms in Metrology (VIM)[20] as "Property of the result of a measurement or the value of a standard whereby it can be related to stated references, usually national or international standards, through an unbroken chain of comparisons all having stated uncertainties." From this definition, it is clear that traceability can only be obtained when uncertainties are determined. The traceability hierarchy in Rockwell hardness from highest level to the hardness measurement is the following:

(1) *International definition of hardness:* This is similar to a "fundamental property value." This definition should precisely define all aspects of the hardness test.

(2) *National definition of hardness:* At this time, there is no international agreement on a well-defined definition for any Rockwell hardness scale. National definitions are used instead, which are based on national and international test method standards. These definitions vary from country to country. The U.S. national definition of Rockwell hardness, as defined by NIST, is based on the use of the NIST primary reference standardizing machine with a specific indenter and following a specific testing cycle[15].

(3) *Primary reference standardizing machine:* A primary reference standardizing machine is usually maintained at a country's National Metrology Institute (NIST in the United States). The design and operation of this machine is dependent on the hardness definition. The NIST primary reference standardizing machine is shown in Figure 11.

(4) *Primary reference test blocks:* The primary reference test blocks are calibrated using the primary reference standardizing machine in accordance with the hardness definition.

(5) *Secondary standardizing machine:* The design and operation of this machine is based on the hardness definition and calibrated using primary reference test blocks.

(6) *Secondary standardized test blocks:* The secondary standardized test blocks are calibrated using the secondary hardness machine in accordance with the hardness definition.

(7) *Laboratory hardness test machine:* The design and operation of this machine is based on the hardness definition and calibrated using standardized test blocks.

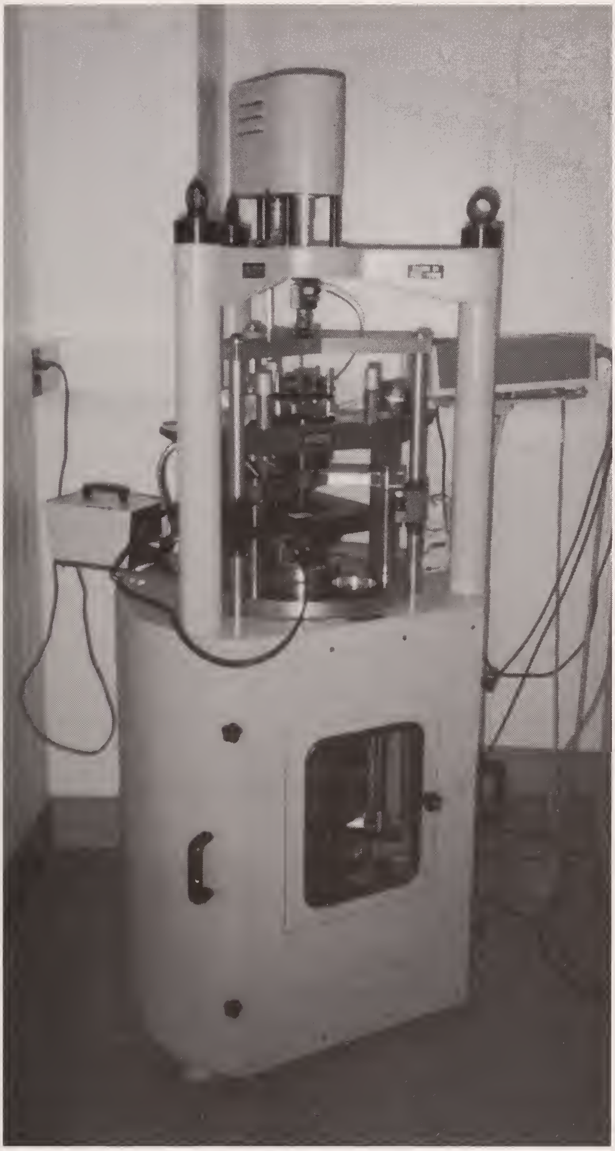


Figure 11.
NIST Rockwell hardness standardizing machine.

(8) Laboratory hardness measurement: The measurement is made based on the hardness definition, using the laboratory hardness test machine.

Two possible traceability scenarios for Rockwell hardness are: (1) to achieve traceability to known reference standards such as reference standards maintained at NIST; and (2) to achieve traceability based on hardness machine errors with respect to the Rockwell hardness definition. In the first scenario, a standardizing laboratory or a testing laboratory bases its measurement uncertainty on measurement comparisons using standardized reference test blocks. Traceability can then be linked to the highest reference level in the traceability hierarchy through one or more reference levels. In the second scenario, a standardizing laboratory's measurement traceability is with respect to the Rockwell hardness definition and is based on standardizing machine errors as defined by the definition. This is the method that is used in determining the measurement uncertainty of primary reference standardizing machines.

8.2 Measurement Error

The Rockwell hardness test is usually thought of as a method that measures the hardness of a material. A more accurate description might be that the Rockwell hardness test only provides an estimate of the absolute "true" hardness value. It is only an estimate since, like essentially all measurement systems; there is always some level of error in a Rockwell hardness measurement. For a hardness measurement to be useful, the level of error must be small enough to meet the user's needs.

The total error in a measurement is often the result of a combination of errors from multiple sources. In the case of a Rockwell hardness machine, errors associated with machine components, testing cycle variations, and environmental conditions, as well as other sources, contribute in varying degrees to the overall measurement error. When it is practical, the measurement result should be corrected for these errors. However, in many cases, the errors may occur randomly and cannot be corrected. In other cases, the errors may be systematic, but there may be valid reasons for not correcting these errors. Even when corrections are made to compensate for the errors, there will be an additional error associated with the correction. These uncorrected errors then account for an "uncertainty" in the accuracy of the measurement result. To have confidence that the result of a hardness measurement is appropriate for a particular application, some understanding of the level of uncertainty in the measurement must be known.

8.3 Uncertainty

The determination of uncertainty associated with Rockwell hardness measurements is a relatively new concept for many users of Rockwell hardness as well as for laboratories engaged in hardness calibrations, such as test block standardizing agencies. Traditionally, the acceptance criterion for Rockwell hardness measurements has been through the use of acceptability tolerances. This has been true for most all aspects of the Rockwell method including measurements made as part of the direct and indirect verifications of hardness machines and the standardization of test blocks.

Tolerance limits will continue to be used in Rockwell hardness. They provide general criteria for determining whether a Rockwell hardness machine is operating at an acceptable level of performance. What the acceptability tolerance limits do not indicate is the accuracy in the measurements made with the hardness machine. When it is important that the measurement accuracy be known, then the uncertainty in the measurements should be determined.

8.3.1 Uncertainty Limits

Uncertainty values are usually written as numerical limits bracketing the measurement value. Stating a measurement value in this way tells the user that the "true value" of the measurement would fall somewhere within these uncertainty bounds. As an example of uncertainty as it might apply to Rockwell hardness, consider a standardized hardness block that is certified with a value of 25.3 HRC ± 0.4 HRC. In this example, the 25.3 HRC value is the certified average hardness of the block, and the ± 0.4 HRC is the uncertainty in this certified value. This means that although the standardizing agency estimated the average hardness value of the test block to be 25.3 HRC, the "true value" would fall somewhere within 24.9 HRC to 25.7 HRC. For a complete understanding of this measurement and uncertainty, the values should be accompanied with a brief statement defining what the uncertainty interval represents. This statement should usually indicate the statistical process used to calculate the uncertainty and state the confidence level of the uncertainty interval.

It is important to understand the difference between uncertainty intervals, such as given in the example above, and acceptance tolerance limits traditionally provided with commercial test blocks. In the example above, the ± 0.4 HRC states that the standardizing agency can only estimate the "true" average hardness of the test block and that the "true value" falls somewhere within ± 0.4 HRC of 25.3 HRC. In contrast to these uncertainty limits, the certified value marked on commercial test blocks in the United States has included tolerance limits that reflect an ASTM acceptability requirement. This requirement states that when using the test block to conduct an indirect verification or daily check of a hardness machine, the machine's measurement value must fall within these limits. As a rule, the acceptance tolerances have been stated in the same format as demonstrated above for uncertainty statements, for example 25.3 HRC ± 1.0 HRC. These are clearly two different concepts.

8.3.2 Highest Reference Standard

Before the level of uncertainty can be determined, the laboratory must choose a reference standard to which the measurement value will be compared. For example, the level of error in a Rockwell hardness machine might be determined by comparing the result of a measurement made on a standardized test block with the test block's certified hardness value. It then follows that the certified value of the test block also includes a level of error with respect to another reference standard, typically the performance of the hardness machine used to standardize it. The performance of the standardizing hardness machine also includes a level of error with respect to a higher-level reference standard, and so it goes to the highest level of reference.

The highest level of reference to which a measurement value is compared might be referred to as the "true value." The level of error in the measurement is then determined with respect to this "true value" taking into account the errors at each of the reference levels between the measurement value and the "true value". Ideally, the highest level of reference should be an internationally agreed upon standard. In some cases, international agreement does not exist; consequently national reference standards (i.e., NIST in the United States) are typically considered the highest reference level. At present, this is the case for Rockwell hardness.

8.3.3 Calculation of Rockwell Hardness Uncertainties

Over the past decade, there has been an increasing industry trend towards obtaining quality program accreditation, as well as obtaining accreditation for testing and calibration facilities. A common element of most of these programs is the requirement for reporting the uncertainty of measurement data. As a result, users of Rockwell hardness have struggled to develop procedures to determine the uncertainty of Rockwell measurements.

Currently, there are no generally agreed upon U.S. or international methods for calculating the measurement uncertainty of a Rockwell hardness machine or the uncertainty in the certified value of standardized test blocks. A reason for this may be that, until recently, there has been very little desire or need by industries that use Rockwell hardness to use uncertainty values. Also, the determination of Rockwell hardness uncertainty is not as straightforward as it would seem.

For example, suppose the uncertainty is to be calculated by combining all of the sources of error together. The errors associated with the hardness machine are typically not in hardness units, but they are in other units, such as force, length, and time. In order to determine an uncertainty in the hardness measurement, the relationships between how these errors affect the hardness value must be determined, often by experiment. Amplifying this problem is the fact that these relationships vary by Rockwell scale and hardness level and are often material dependent. In addition, the errors associated with a diamond indenter are difficult to identify and more difficult to relate to errors in hardness. Thus, it is clear that determining the hardness uncertainty by assessing the individual components of the hardness machine is extremely difficult to accomplish.

A different approach to determining Rockwell hardness uncertainty is to assume that by passing a direct and indirect verification, the errors in the individual operating components of the hardness machine are small enough that the indirect verification measurements are not the result of multiple large errors offsetting each other. Thus, the individual machine components can be considered to be operating together as a single component. The individual operating components include the force application system, depth measuring system, indenter, test cycle, and the remaining parts of the machine frame and test specimen support system. By considering the hardness machine as a single component, the uncertainties may be estimated with respect to the overall performance of the hardness machine without having to assess the uncertainty contributions for each of the separate machine components. When this approach is used, the most significant sources of error have been determined to be the following:

(1) Repeatability in the performance of the hardness machine.

(2) Reproducibility in the day-to-day performance of the hardness machine, including operator influence.

(3) Resolution of the measurement indicating display.

(4) Uncertainty in the certified average hardness value of the reference test block.

(5) Non-uniformity in hardness across the surface of the test block or test material.

(6) Bias in the hardness machine measurement with respect to the reference standard to which traceability is claimed.

(7) Determining the hardness machine measurement bias.

(8) Correcting for the measurement biases.

(9) The remaining bias in the hardness machine after a correction for bias is made.

As this guide is being written, there are efforts both internationally and within the United States to develop general procedures to assist Rockwell hardness standardization laboratories and users of Rockwell hardness in evaluating their measurement uncertainty. In the United States, the ASTM has initiated the development of such a procedure, and the ISO is to take up this issue at the next committee meeting of ISO TC164/SC 3 subcommittee on hardness testing in 2001.

9 STATUS OF ROCKWELL HARDNESS STANDARDIZATION IN THE YEAR 2000

9.1 United States

The past few years have seen significant changes to Rockwell testing in the United States with the introduction of NIST Rockwell standards, accreditation of Rockwell calibration laboratories, and the increased need to determine measurement uncertainty. Although the changes may not yet have impacted many users of Rockwell hardness, these and other proposed changes should soon affect every level of testing and will hopefully improve the accuracy and consistency of Rockwell measurements throughout the nation's industries.

9.1.1 NIST Standards

In 1991, NIST began the development of a national Rockwell hardness standardization laboratory at the urging of the ASTM and U.S. industry. The goals of this program are to standardize the Rockwell hardness scales for the United States 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. The blocks are available to anyone wishing to purchase them; however, they are primarily intended for use by the secondary Rockwell hardness calibration laboratories.

A significant result of the NIST standardization of the HRC scale is that the hardness levels of the NIST HRC scale deviated from the HRC scale used by U.S. industry at that time. The magnitude of the deviation varies by hardness level and also depends on which calibration agency's reference test blocks had been used previously. Figure12 demonstrates the general trend of the difference between NIST and U.S. industry HRC scales. The offset trend given in Figure 12 should not be used as an absolute offset. The relationship could possibly differ by as much as ± 0.5 Rockwell points; however, it is generally true that the greatest offset is at the high end of the scale. Also of interest is that the NIST HRC scale is in good agreement with other countries worldwide (see 9.2 below).

The next Rockwell scale for which NIST will release test blocks is the Rockwell B scale, likely followed by the HRA, HRN, and HRT scales. Eventually NIST hopes to provide a means for traceability to all Rockwell scales.

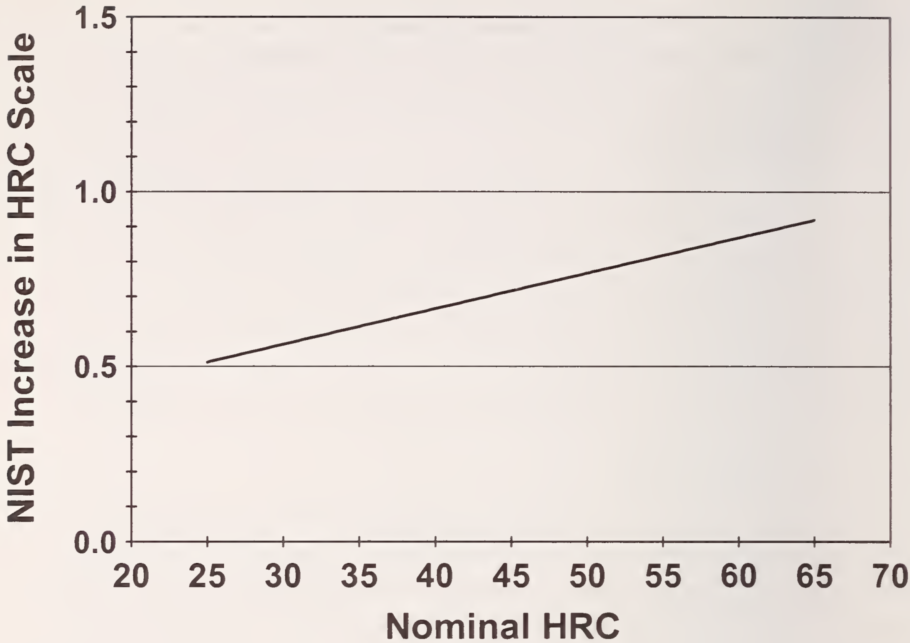


Figure 12.

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.

9.1.2 ASTM Test Method Standards

The ASTM Subcommittee E28.06 on Indentation Hardness Testing is always striving to improve the Rockwell hardness test. Subcommittee members are from industry and government, and they include manufacturers and users of Rockwell hardness equipment. Much of the effort to improve the Rockwell test has been through the requirements of the ASTM E18 Rockwell hardness test method[(2)]. A significant revision was recently made to the standard requiring that performance verifications of Rockwell hardness indenters and hardness machines must be made using test blocks calibrated traceable to the Rockwell standards maintained by NIST. This can be accomplished through the use of commercial test blocks calibrated traceable to the NIST standard or by directly using the NIST SRMs. The new requirement will apply only to the Rockwell scale(s) for which NIST supplies primary reference test blocks. As NIST develops new SRMs for other Rockwell hardness scales, the same requirement will apply for those scales.

Currently, the ASTM hardness subcommittee also is developing a major revision of the E18 Rockwell hardness standard. The intention of the revision is to improve E18 by: clearly specifying when traceability is achieved; clarifying requirements and procedures; revising procedures to reflect current practice; and adding requirements and procedures to improve the Rockwell hardness test method.

The increasing need by industry to report uncertainties has led the ASTM hardness subcommittee to initiate the development of a general procedure for determining uncertainty in Rockwell hardness measurements. The procedure is being developed to assist hardness standardization, calibration, and verification laboratories by providing a basic approach to evaluating their uncertainty in order to simplify and unify the interpretation of uncertainty by users of Rockwell hardness.

9.1.3 Hardness Industry

Most U.S. secondary laboratories engaged in the manufacture and calibration of Rockwell hardness equipment are now producing Rockwell HRC test blocks and diamond indenters that are certified traceable to the NIST HRC reference test block standards. This has resulted in some users having to obtain a new Rockwell diamond indenter in order for their hardness machine to pass indirect verification of the HRC scale using NIST traceable HRC test blocks.

9.1.4 Accreditation

An increasing number of domestic and international customers of calibration and testing agencies are requiring that calibrations and measurements made by these agencies be traceable to national reference standards when possible, and, in many cases, that the laboratories be accredited to perform these measurements. This applies to the Rockwell hardness industry as well. Consequently, commercial and governmental programs have been developed for accrediting laboratories engaged in Rockwell hardness testing and calibrations.

9.2 International

International harmonization of the Rockwell hardness scales is yet to occur. This is due to several factors, the most significant being differences in the testing cycles used by the National Metrology Institutes (NMIs) throughout the world and, in the case of the diamond indenter scales, differences in the performance of the national indenters used by the NMIs[(21)]. The need for international harmonization is well recognized, and there are efforts to achieve this goal currently being made under the auspices of the International

Committee for Weights and Measures (CIPM) and, to some degree, by the ISO and OIML.

9.2.1 BIPM and CIPM

The Bureau International des Poids et Mesures (BIPM) [International Bureau of Weights and Measures] was set up by the Convention of the Metre, a diplomatic treaty that was signed in 1875. Under the terms of the Metre Convention, the BIPM is financed jointly by the Member States of the Convention and operates under the exclusive supervision of the Comité International des Poids et Mesures (CIPM) [International Committee of Weights and Measures]. The BIPM headquarters is located in Sèvres, France, near Paris.

The CIPM is made up of eighteen individuals, each from a different Member State. Its mandate is to provide the basis for a single, coherent system of measurements throughout the world, traceable to the International System of Units (SI). This task takes many forms, from direct dissemination of units (as in the case of mass and time) to coordination through international comparisons (key comparisons) of national measurement standards (as in length, electricity, radiometry, and ionizing radiation). It operates through a series of Consultative Committees, whose members are the national metrology laboratories of the Member States of the Convention, and through its own laboratory work. The CIPM meets annually at the BIPM and discusses reports presented by its Consultative Committees. Reports of the meetings of the CIPM, and all the Consultative Committees, are published by the BIPM.

In 1998, a new ad-hoc working group was formed under the CIPM to investigate the present state and needs for international comparisons of hardness standards and report to the CIPM on the most appropriate platform for the comparison, if it is really necessary. The working group was given the name Ad-Hoc Working Group on Hardness (AHWGH) and was comprised of members representing ISO, OIML, the International Measurement Confederation (IMEKO), and National Metrology Institutes having a strong standardization program. Since its inception, the group determined that international comparisons of hardness standards are important and necessary. Consequently, in October 1999, the working group was officially approved as the Working Group on Hardness (WGH) and has been placed under the Consultative Committee on Mass (CCM).

Current efforts by the WGH include the adoption of a recent world-wide intercomparison of Rockwell hardness scales using a diamond indenter as an international key comparison, the initiation of a study on the shape measurement of diamond Rockwell indenters, and the initiation of a key comparison of Vickers hardness. An example of the results of the worldwide

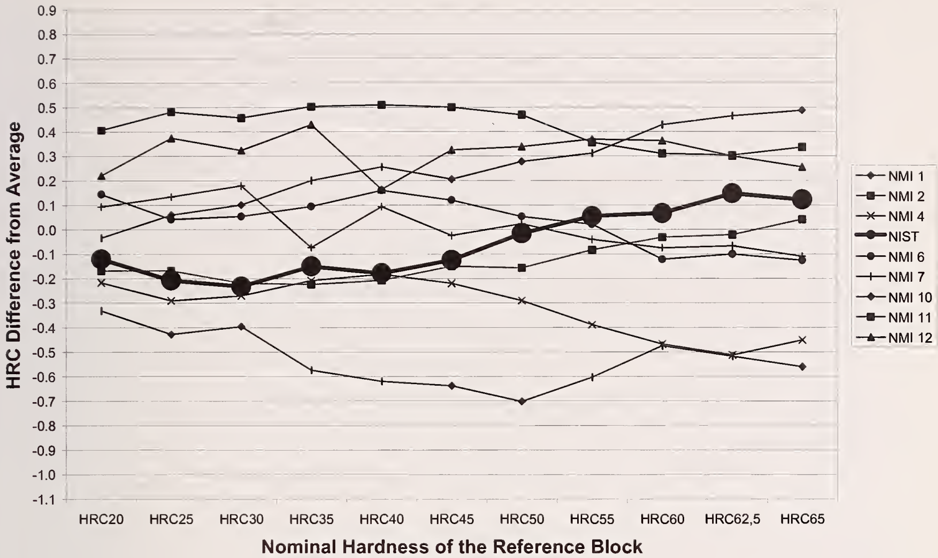


Figure 13.

Results of 1999 international comparison of HRC scale.
The heavy line indicates the NIST data.

intercomparison(22) is shown in Figure 13 for the Rockwell C scale. The participants in the comparison were national metrology institutes throughout the world, including NIST. As the figure illustrates, there continues to be significant differences between the world's national hardness scales.

9.2.2 ISO

The ISO technical committee on hardness testing, ISO TC164/SC3, is comprised of hardness experts representing their nations' standards organizations. The schedule for review and revision of test method standards is usually every five years; however, the committee meets each year to discuss changes and improvements to the hardness tests, based on the latest technical information presented by the delegations. The latest revisions of the Rockwell hardness test method standards ISO 6508-1(3), ISO 6508-2(4), and ISO 6508-3(5) were published in 1999.

9.2.3 OIML

The current OIML Recommendations related to hardness testing are under revision at this time. The Recommendation R39 (1981), concerning the verification of Rockwell hardness machines will be the initial document to be revised.

10 BIBLIOGRAPHY

1. Lysaght, V.E., Indentation Hardness Testing, Reinhold Publishing Corp., New York, 1949, pp. 57-105.

2. ASTM E 18 – 2000, Standard Test Methods for Rockwell Hardness and Rockwell Superficial Hardness of Metallic Materials, West Conshohocken, PA, ASTM, 2000.

3. ISO 6508-1 Metallic Materials – Rockwell hardness test (scales A, B, C, D, E, F, G, H, K, N, T) – Part 1: Test method, Geneva, International Organization for Standardization, 1999.

4. ISO 6508-2 Metallic Materials – Rockwell hardness test (scales A, B, C, D, E, F, G, H, K, N, T) – Part 2: Verification of testing machines, Geneva, International Organization for Standardization, 1999.

5. ISO 6508-3 Metallic Materials – Rockwell hardness test (scales A, B, C, D, E, F, G, H, K, N, T) – Part 3: Calibration of reference blocks, Geneva, International Organization for Standardization, 1999.

6. OIML International Recommendation No. 12 (1974), Verification and calibration of "Rockwell C" hardness standardized blocks.

7. OIML International Recommendation No. 36 (1976), Verification of indenters for hardness testing machines (Systems: Brinell – Rockwell B, F, and T – Vickers – Rockwell C, A, and N).

8. OIML International Recommendation No. 39 (1981), Verification of hardness testing machines (Rockwell B, F, T – C, A, N systems).

9. OIML International Recommendation No. 11 (1974), Verification and calibration of "Rockwell B" hardness standardized blocks.

10. Liggett, W.S., Low, S.R., Pitchure, D.J., and Song, J., "Capability in Rockwell C Scale Hardness," *Journal of Research of the National Institute of Standards and Technology*, Volume 105, Number 4, July–August 2000, pp. 511–533.

11. Metals Handbook, 8th Edition, Vol. 11, Nondestructive Inspection and Quality Control, H.E. Boyer, editor, American Society for Metals, pp. 1–13.

12. Metals Handbook, Ninth Edition, Vol. 8, Mechanical Testing, Rockwell Hardness Testing, A.R. Fee, R. Segabache, E.L. Tobolski, American Society for Metals, pp. 74–83.

13. Metals Handbook, Desk Edition, H.E. Boyer and T.L. Gall, editors, American Society for Metals, Hardness Testing, pp. 34–4 to 34–8, 1985.

14. Low, S.R., Pitchure, D.J., Flanigan, C.D., "The Effect of Suggested Changes to the Rockwell Hardness Test Method," *Proceedings of XVI IMEKO World Congress*, eds. Osanna, P., Durakbasa, A., Afjehi-Sadat, A., (2000), pp. 313–318.

15. Low, S.R, Gettings, R.J., Liggett, Jr., W.S., Song, J., Rockwell Hardness – A Method-Dependent Standard Reference Material, *Proceedings of the 1999 Workshop and Symposium (Charlotte, NC, 11–15 July 1999)*, Charlotte, NC, 1999.

16. Petik, F., Factors Influencing Hardness Measurement (A Systematic Survey of Research Results), Bureau International de Metrologie Legale, Paris, 1983 (restricted distribution).

17. ASTM E 140 – 97, Standard Hardness Conversion Tables for Metals, West Conshohocken, PA, ASTM, 2000.

18. NIST Standard Reference Materials Catalog 1998–99, NIST Special Publication 260, Trahey, N.M., editor, Gaithersburg, MD, January 1998.

19. Low, S.R., Liggett, W.S., Pitchure, D.J., "A New Method of Certifying Standardized Rockwell Hardness Test Blocks," *Proceedings of International Symposium on Advances in Hardness Measurement*, Standards Press of China, Beijing, China, 1998, 91–96.

20. BIPM / IEC/ IFCC / ISO / IUPAC / IUPAP / OIML: International Vocabulary of Basic and General Terms in Metrology (VIM), Clause 6.10, 1993.

21. Song, J.F., Low, S., Pitchure, D., Germak, A., Desogus, S., Polzin, T., Yang, H.Q., Ishida, H., Barbato, G., "Establishing a World-Wide Unified Rockwell Hardness Scale With Metrological Traceability," Metrologia, 1997, 34, 331–342.

22. Polzin, T., Schwenk, D., contributions from He Li, Hansen, V., Herrmann K., Barbato, G., Germak, A., Ishida, H., Onsinska-Karczmarek, A., Scartazzini, W., Borovsky, J., Elkington, D., Low, S., Song, J., Bahng, G.W., World-Wide Unified Scales for the Rockwell Hardness Test with Conical Indenters, Results of the round robin test, differences between the laboratories, Materialprüfung, (42), 2000, S. 460–467.

ANNEX A: APPLIED FORCE EFFECT

The magnitude of change in the Rockwell hardness value that results from a change in the applied force is shown in Figure A.1 for the preliminary force and in Figure A.2 for the total force. The test method standards published by ASTM and ISO provide tolerances for the applied Rockwell forces. Summaries of these tolerances are given in Table A.1. Figure A.3 illustrates the possible variation in Rockwell hardness measurement values that can be obtained for the diamond indenter scales while maintaining the forces within the specified tolerances.

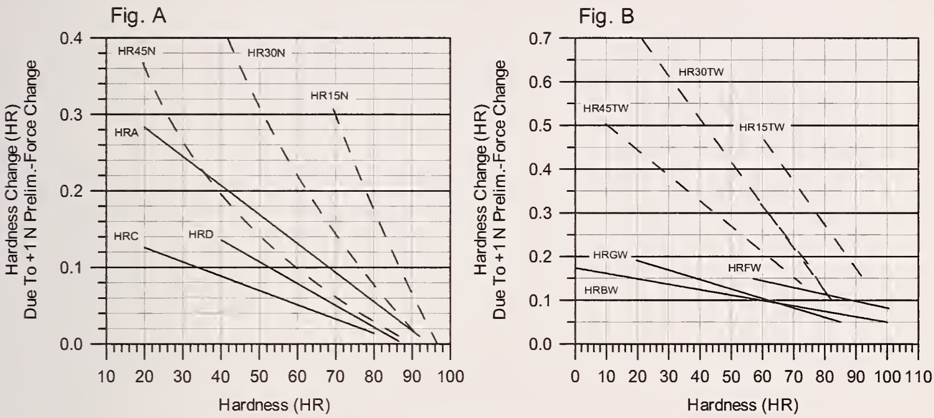


Figure A.1.

Change in the Rockwell hardness value due to a change in the preliminary force for diamond indenter scales (Figure A) and selected ball scales (Figure B).

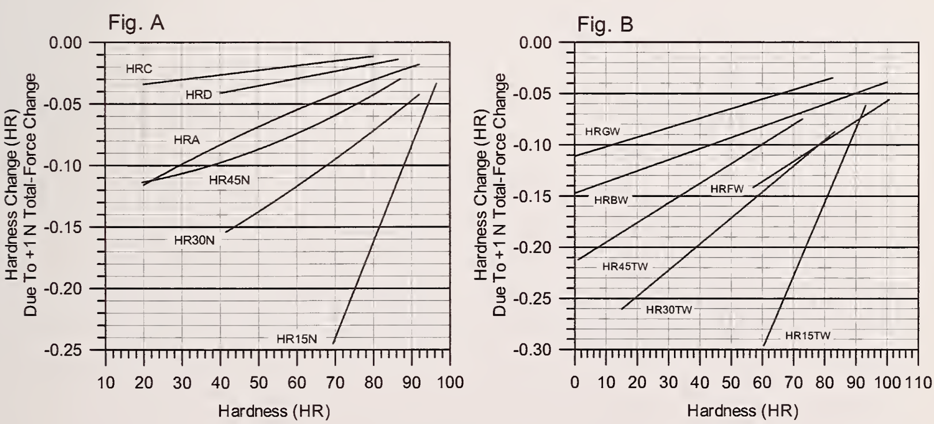


Figure A.2.

Change in the Rockwell hardness value due to a change in the total force for diamond indenter scales (Figure A) and selected ball scales (Figure B).

Table A.1.

Specified test forces with tolerances

Test forces N (kgf)	ASTM Tolerances on Applied Forces N	ISO Tolerances on Applied Forces N
98.07 (10)	± 1.96	± 1.96
588.4 (60)	± 4.41	± 5.88
980.7 (100)	± 4.57	± 9.81
1471 (150)	± 8.83	± 14.71
29.42 (3)	± 0.589	± 0.588
147.1 (15)	± 0.981	± 1.471
294.2 (30)	± 1.961	± 2.942
441.3 (45)	± 2.943	± 4.413

Fig. A: ASTM

Fig. B: ISO

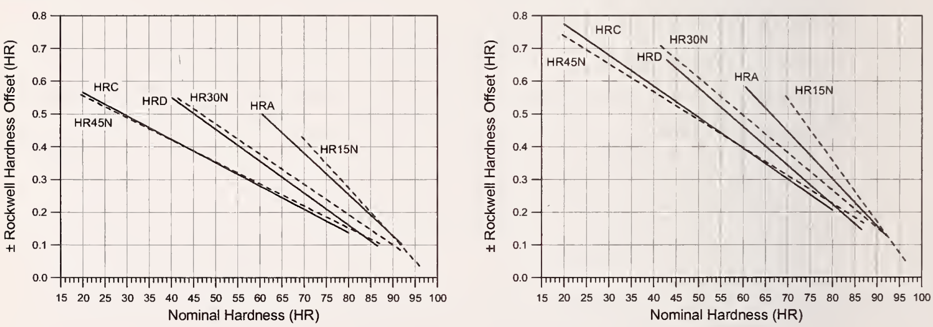


Figure A.3.

The possible offset in Rockwell hardness measurement values that could be obtained for the diamond indenter scales by varying the applied preliminary forces and total forces within the ASTM tolerances (Figure A) and the ISO tolerances (Figure B).

ANNEX B: ROCKWELL HARDNESS TESTING CYCLE EFFECT

To better understand the Rockwell hardness testing cycle, imagine it divided into eight parts or steps, as illustrated previously in Figure 3. These eight testing cycle steps are defined as either a time period or an indentation velocity, each of which can be varied. They are:

1. the contact velocity of the indenter at the point of contact with the test material;
2. the preliminary force application rate as the preliminary force is applied;
3. the preliminary force dwell time, the time period from the onset of reaching the preliminary force until the first baseline depth of indentation is measured;
4. the additional force application rate as the additional force is added to the preliminary force to obtain full application of the total force;
5. the total force dwell time, the time period during which the total force is fully applied;
6. the additional force removal rate as the additional force is removed, returning to the preliminary force level;
7. the recovery dwell time, the time period from when the additional force is fully removed, until the second and final depth of indentation is measured; and
8. the preliminary force removal rate as the preliminary force is removed.

With the exception of step 8, which has no influence on the hardness measurement, all of the testing cycle steps can affect the hardness result to some degree, some considerably more than others. The extent of the possible range in hardness values depends on which steps of the testing cycle are varied and the amount of the change, and on the hardness level and flow properties of the material under test. Both an increase and decrease in the hardness measurement value can occur by changing any one of the testing cycle steps. It is also possible that by varying two or more steps of the testing cycle, the respective effects can offset the others and result in essentially no change in the measured hardness. The testing cycle steps that are considered to have the greatest effect on the hardness measurement result are typically specified by the Rockwell hardness test method standards. Also, newer commercial hardness testers are often pre-programmed by the manufacturer with a default testing cycle, defining two or more of these variables.

The effect that each of the eight test-cycle steps has on the hardness result can be divided into two categories: (1) indenter velocity or force application rate effect; and (2) dwell time effect. Steps 1, 2, 4, 6, and 8 fall under the first category. The effect of obtaining different measurement values by varying one or more of these five testing cycle steps is due either to rate sensitivity of the material under test or to the dynamics of the hardness tester. The remaining three parts of the testing cycle, steps 3, 5, and 7, fall into the second category defined as dwell times. Each of the three dwell time steps affect the hardness result because of creep and elastic recovery of the test material which occurs during these periods of constant force levels. The relative effect that each of the eight test-cycle steps has on the Rockwell hardness result are discussed below by presenting data from actual Rockwell hardness measurements. The information is presented to illustrate trends only since the effect of each testing cycle step will vary depending on the hardness scale and the specific material tested.

B.1 Effect of Force Application Rate

For each of the five steps [1, 2, 4, 6, and 8] in this category, an excessive indenter velocity or force application rate may adversely affect the Rockwell measurement. The applied forces can overshoot the specified levels due to dynamic effects, or cyclic vibration may be introduced into the force application mechanism. Test method standards usually only specify steps 1, 2, 6, and 8 to be accomplished "without shock or vibration." When a reasonable testing speed is used, the magnitude that these testing cycle steps affect the hardness result is typically negligible as compared to the effects produced by varying the dwell time variables. In addition to the effect caused by excessive force application rates, the measurement result may also be affected due to rate sensitivity of the test material. For most of the five test-cycle steps, the rate sensitivity effect is negligible with the exception of testing cycle step 4, the additional force application velocity. For many metallic materials, variations in the rate of applying the additional force have been shown to have a significant measurable effect on the resultant Rockwell value.

During testing cycle steps 2, 4, 6, and 8, forces are being applied or removed from the indenter as it produces the indentation in the test material. Because of differences in the design and operation of hardness machines, in many cases the indenter velocity or force application rate is not constant during the entire period of a testing cycle step. Also, it is often difficult to accurately measure the velocity of the indenter during a hardness test. Thus, in cases where these testing cycle steps are specified in standards, a time period is sometimes specified rather than indenter velocity.

B.1.1 Step 1 – Contact Velocity of the Indenter

The effect on hardness caused by testing cycle step 1, the contact velocity of the indenter at the point of contact with the test material, is primarily due to dynamic effects of the indenter. An excessive contact velocity could cause the preliminary force level to be exceeded if the indenter cannot decelerate and stop when the preliminary force is applied, or, more likely, the indenter may impact the test material setting up a cyclic vibration in the hardness tester. Each of these circumstances may vary the hardness result.

B.1.2 Step 2 – Application of the Preliminary Force

The preliminary force application, testing cycle step 2, may be specified in terms of the velocity of the indenter from initial contact of the indenter with the test material, to the full application of the preliminary force level. It also may be specified in terms of the period of time for applying the preliminary force. During testing cycle step 2, the extent of indenter displacement is relatively small, and for most commercial hardness testers, this operation occurs fairly rapidly. An exception is that manually operated hardness testers allow the user to easily vary the rate at which this testing cycle step occurs. For this part of the testing cycle, any effect on the hardness result that might be due to rate sensitivity of the test material has not been extensively investigated. It is usually considered to be negligible in comparison with other testing cycle steps. There is some evidence, however, that when longer time periods are used to apply the preliminary force, significant material creep can occur during the force application which may alter the test material creep behavior during the preliminary force dwell time (testing cycle step 3) and, thus, affect the hardness result.

B.1.3 Step 4 – Application of the Additional Force

The additional force application testing cycle step is defined as starting when the additional force begins to be added to the preliminary force and ends when the total force is achieved. Unlike the four other testing cycle steps grouped in this category, tests have shown that the rate at which the additional force is applied may significantly affect the Rockwell measurement. Often, neither the indenter velocity nor the rate that the force is applied is constant during the entire additional force application but, instead, varies during this period. In these cases, it is typical that the velocity or rate is rapid at the onset and then slows in the last part of the force application. It is very important that the velocity or rate not be so fast that dynamic effects produce a momentary overshoot of the total force level or set up oscillations in the force application mechanism. Figure B.1 illustrates the type of force and indenter depth oscillations that can occur when the force application rate is too fast.

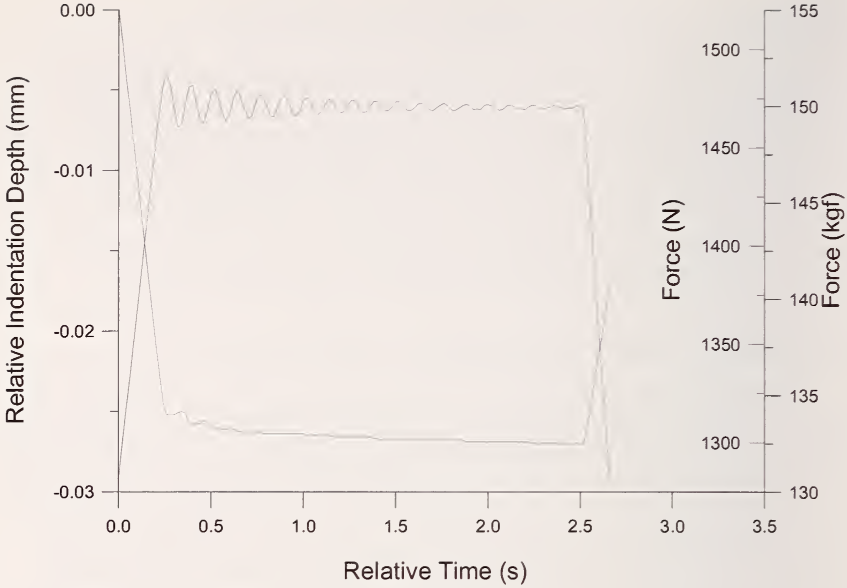


Figure B.1.

Force and indenter depth oscillations that can occur when the force application rate is too fast.

Tests have shown that by varying the indenter velocity used for the additional force application, different Rockwell hardness results can be obtained. It is believed that the velocity effect is more significant during the final part of the force application. It is not clear, at this time, what mechanism causes the change in Rockwell results when the force application rate is varied. It may be due to the material's ability to creep during very slow applications of force. An example of this velocity effect is shown in Figure B.2 for a material of 50 HRC. This figure shows tests made using indenter velocities ranging from 0.5 to 70 µm/s on a test block having a hardness of approximately 50 HRC. For this material, the largest differences in hardness measurement results occurred for tests made with the very slowest velocities (<10 µm/s). The measurement results were more constant as the velocity was increased. As a point of reference, commercial hardness testers often run at velocities of about 100 µm/s, although many slow at the last part of the force application.

B.1.4 Step 6 – Removal of the Additional Force

The magnitude of the effect that removal of the additional force (testing cycle step 6) has on the hardness result is similar to that of testing cycle step 2. As

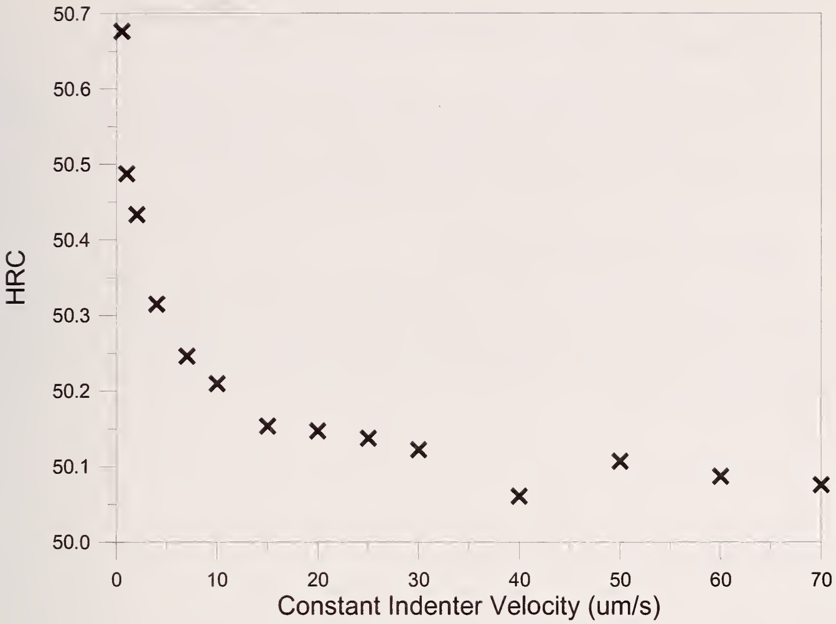


Figure B.2.

Change in apparent HRC hardness due to changes in the additional force application rate (indenter velocity).

the additional force is removed, the amount of elastic recovery of the material and, thus, indenter displacement is relatively small. For most commercial hardness testers this operation is fixed to occur fairly rapidly, although manually operated hardness testers may allow the user to manually vary this time period. Again, as with testing cycle step 2, the effect that this part of the testing cycle has on the hardness result has not been closely examined. The effect is usually considered to be negligible, even more insignificant than any effect due to the preliminary force application rate. However, if a very slow unloading rate were utilized, the material would continue to creep under the higher force levels until the additional force was completely removed. The added time under the higher force could affect the hardness result in this case.

B.1.5 Step 8 – Removal of the Preliminary Force

Testing cycle step 8, removal of the preliminary force, occurs after the two depth measurements have been made that are used in the determination of the hardness result. Varying this part of the testing cycle has no effect on the hardness result.

B.1.6 Summary – Indenter Velocity and Force Application Times Effects

The testing cycle steps grouped in this category have been shown to contribute to the resulting hardness measurement value. This is particularly true for testing cycle step 4, the application of the additional force.

B.2 Effect of Dwell Times

As an aid to this discussion, indentation depth data will be presented for each of the three dwell times. The data will be displayed by greatly expanding the indenter depth axis and magnifying the area of the testing cycle of interest as illustrated in Figure B.3.

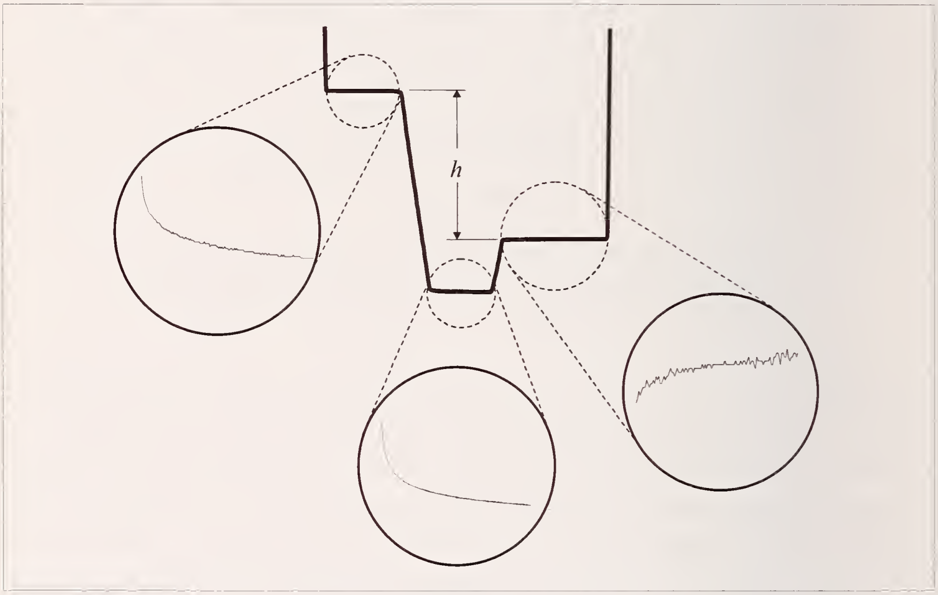


Figure B.3.

Expanded view of the material creep and recovery during the dwell times of a Rockwell hardness test.

B.2.1 Step 3 – The Preliminary Force Dwell Time

As stated above, the preliminary force dwell time is defined as the dwell time from the onset of reaching the preliminary force level until the first baseline depth of indentation is measured. In other words, during this dwell time period, the force on the indenter is held constant at the preliminary force level. At the end of the preliminary force dwell time, the depth of indentation is measured which will be used in the calculation of the hardness number. While under the constant force, if the depth of the indenter is not stable but, instead, continues to creep into the test material, then the measurement value of the indentation depth will vary with time. Thus, the first baseline depth measurement that is used in the calculation of the HRC value will depend on how long after reaching the preliminary force level the measurement is made (i.e., the preliminary force dwell time). Since the calculation of Rockwell hardness is based directly on this depth measurement, then any change in the preliminary force dwell time will directly affect the resulting hardness value.

Tests have shown that indentation continues during the preliminary force dwell time due to plastic flow in the test material. Figure B.4 illustrates the creep behavior of the material for 6.5 seconds after the preliminary force is applied. This data is for tests made on three test blocks of hardnesses 25, 45, and 63 HRC. Since the hardness calculation is based directly on this depth of indentation, the units of the vertical axis showing indenter depth have been converted to an offset in HRC units by simply dividing the indenter depth in mm by 0.002 mm per HRC unit. This was done to give the reader a sense of how much influence the preliminary force dwell time can have on the hardness value. Note that the Y-axis is oriented such that the hardness value increases in the downward direction. The figure clearly shows that the shorter the preliminary force dwell time, the more rapidly there is a change in the HRC hardness value with time, and the lower the hardness result will be.

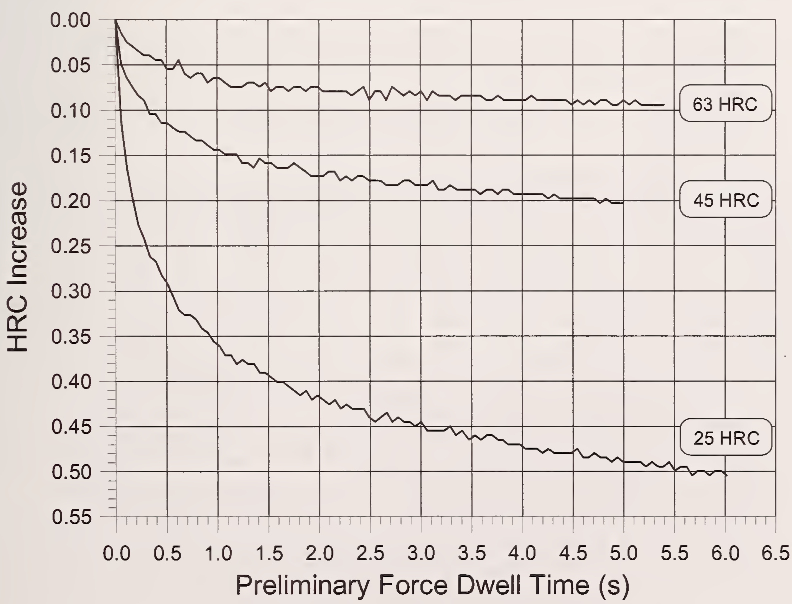


Figure B.4.

Relationship between the preliminary force dwell time and the HRC measurement value for steel test blocks at three hardness levels.

The data also shows that the effect of dwell time is largest at the lower HRC levels. This is because the preliminary force dwell time effect is primarily the result of the plasticity of the material under test. In general, the lower the hardness of a metal, the greater is its ductility or ability to deform plastically.

B.2.2 Step 5 – The Total Force Dwell Time

The total force dwell time is defined as the dwell time during which the total force is fully applied. Again tests have shown that the indenter continues to penetrate into the test material during the total force dwell time. Figure B.5 and Figure B.6 show the creep behavior of the indenter for a period of 5 seconds after the total force is applied for tests made on HRC and HRB test blocks. This data clearly shows that, as with the preliminary force dwell, the shorter the total force dwell time, the more rapid is the change in the hardness value with time. However, in this case, the hardness value increases with shorter dwell times. Note that the Y-axis is oriented such that hardness decreases in the downward direction. As with the preliminary force dwell time, Figure B.5 and Figure B.6 also show that the effect of total force dwell time is largest for the lower hardness levels. This effect is also due to the amount of plasticity exhibited by the material under test. The difference in the shape of the HRC and HRB data curves also suggests that the creep in the material may be dependent on the type of indenter that is used.

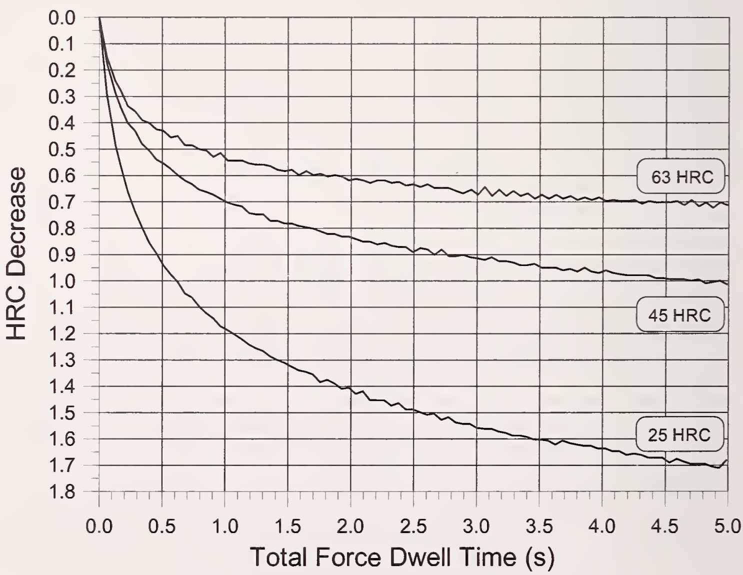


Figure B.5.

Relationship between the total force dwell time and the HRC measurement value for steel test blocks at three hardness levels.

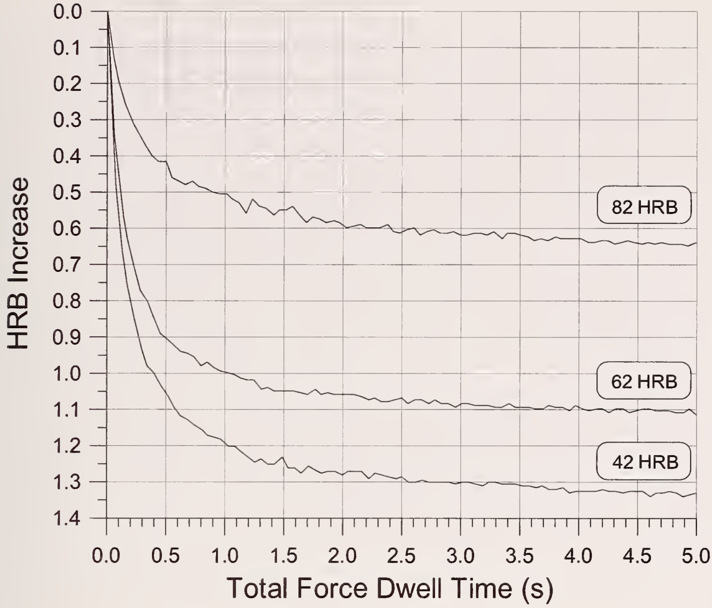


Figure B.6.

Relationship between the total force dwell time and the HRB measurement value for brass test blocks at three hardness levels.

B.2.3 Step 7 – The Recovery Dwell Time

The recovery dwell time is defined as beginning when the additional force is fully removed, returning the force on the indenter to the preliminary force level, and ending when the second and final depth of indentation is measured. As the additional force is removed, the material under load experiences some recovery, primarily elastic although with a small reverse-plasticity component. If when the second and final indentation depth measurement is taken, the material has not fully recovered, then the indenter will continue to be displaced, again resulting in variations in indenter depth measurement with time. The result of this second measurement of indenter depth will depend on how long after reaching the preliminary force level was the measurement made (i.e., the recovery dwell time). Since the calculation of Rockwell hardness is directly based on this depth measurement, then any change in the recovery dwell time will directly affect the resulting hardness value.

Tests have shown that the material does continue to recover to some extent during the recovery dwell time. Figure B.7 illustrates the recovery of the material after the force is returned to the preliminary force level. These tests were made on the same test blocks as discussed previously. Again, the units of the vertical axis showing indenter depth have been converted to an offset in HRC units. Note that the Y-axis is oriented such that hardness increases in the upward direction. The figure shows that the shorter the preliminary force dwell time, the more rapid is the change in the hardness value with time, and the lower the hardness result will be. It should be noted that the data presented here is for the elastic recovery of the test material only. In tests using a commercial tester, there may be elastic recovery in the test machine itself, which could add to this effect. The tests also shows that, unlike preliminary and total force dwell times, the effect of recovery dwell time is largest for the higher hardness levels. In this case, the displacement of the indenter during the dwell time is due primarily to the elastic recovery in the material after the additional force is removed. In general, the higher the hardness of a metal, the lower is its ductility, thus the material retains a higher level of elasticity under load.

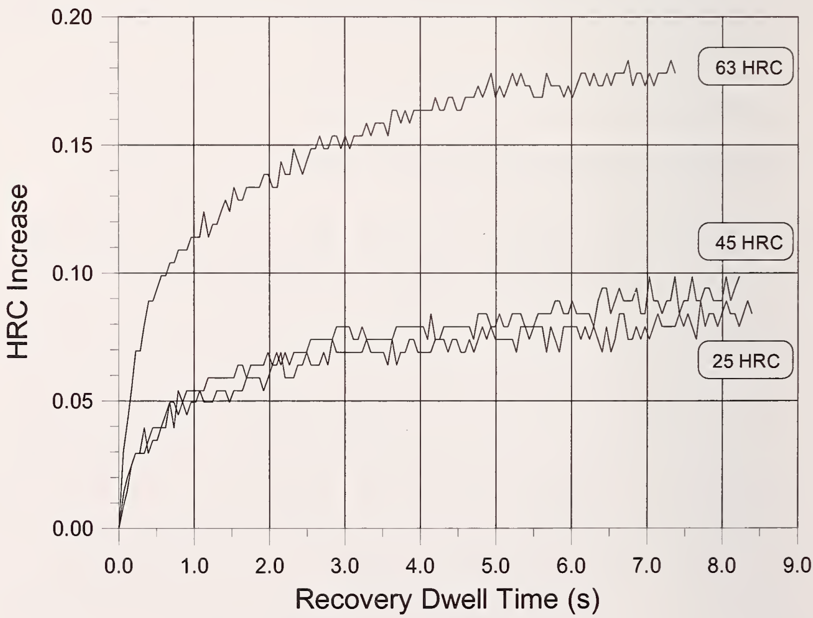


Figure B.7.

Relationship between the recovery dwell time and the HRC measurement value for steel test blocks at three hardness levels.

B.2.4 Summary – Dwell Time Effects

The above discussions demonstrate the relative effect that each of the three dwell times has on the Rockwell hardness value. It is evident that by varying dwell times, all else being equal, the measurement of Rockwell hardness will be affected and will produce different results for each change in a dwell time. The data presented show specific trends in the effects of the dwell times. These can be summarized as follows:

- For each of the three dwell times, the rate of change in the apparent Rockwell hardness value is most rapid during short dwell times, lessening as the dwell times are extended.
- In general, the Rockwell hardness number is most affected by the total force dwell time, followed by the preliminary force dwell time, and then the recovery dwell time. This depends somewhat on the hardness level of the material.

ANNEX C: USE OF NIST ROCKWELL C SCALE SRM TEST BLOCKS

The NIST SRM reference test blocks for the Rockwell C scale (HRC) are certified at three hardness levels; 25 HRC, 45 HRC, and 63 HRC, (SRMs 2810, 2811, and 2812, respectively). Because these test blocks are often used in situations where the highest measurement accuracy is desired, the first part C.1 of this Annex provides recommendations for the proper use of the SRMs. The second part C.2 of this Annex provides formulas for calculating the certified value for any location on the SRM as well as the average hardness of two or more arbitrary locations.

C.1 Recommendations for Use

C.1.1 Test Environment

It is recommended that the Rockwell hardness machine to be calibrated or verified be kept in a temperature and humidity controlled environment maintained at 23 °C ± 2 °C (73 °F ± 5 °F) and a relative humidity of 50 % or less. The hardness machine must be in a location that is free from shock or vibration that could affect the hardness measurements.

C.1.2 Anvil

It is recommended that a flat anvil (i.e., an anvil that can self support the SRM at any test location) should be used with this SRM. However, when the SRM is being used for the calibration or verification of a hardness machine, the same anvil must be used with the SRM (when possible) that will be used subsequent to the calibration or verification.

C.1.3 Seating the Anvil and Indenter

Prior to measuring the SRM, the hardness machine anvil and indenter must be adequately seated. This may be accomplished by performing standard Rockwell hardness tests on a material having a hardness value equal to or higher than the stated value of the SRM. The seating tests should be repeated until the successive measurement values show no trend of increasing or decreasing hardness.

C.1.4 Cleaning the Anvil and Indenter

The hardness machine anvil and indenter diamond tip should be thoroughly cleaned per manufacturer's recommendations. In the absence of manufacturer's cleaning instructions, it is recommended that the anvil and indenter be cleaned with ethyl alcohol and dried using a lint free cloth. Lastly, blow the surfaces clean of dust using filtered air, such as from a commercial compressed air can or bottle. Do not blow clean by mouth.

C.1.5 Cleaning the SRM

Prior to use, it is recommended that the SRM test block be cleaned. A recommended method for cleaning the SRM is to gently wipe the top and bottom SRM block surfaces with clean cotton, thoroughly wetted with ethyl alcohol. The metal surfaces should immediately be dried using a soft lint free cloth or paper towel before the alcohol evaporates in the air. This cleaning must be performed in a manner that prevents a residue from remaining on the top or bottom surfaces. The cleaning should be followed by blowing the surfaces clean of dust using filtered air. The top and bottom surfaces should not be touched after cleaning.

C.1.6 Placement of the SRM on the Anvil

Immediately before placing the SRM on the hardness machine anvil, the top surface of the anvil and the bottom surface of the SRM should be blown free of dust as before. The SRM should be carefully placed on the anvil before dust can return. The top test surface of the SRM block should be blown free of dust prior to testing and occasionally during the period of use. When a flat anvil is used, the SRM block should be slid several times back and forth over the surface of the anvil to help seat the block on the anvil. Any time the SRM is lifted from and replaced on the anvil, the procedure described above in this paragraph should be repeated. When a spot anvil is used (i.e., an anvil having a much smaller diameter than that of the SRM block, requiring the block to be additionally supported when testing at locations other than the block center), extreme care should be practiced to ensure that the test block is supported parallel to the anvil until the indenter contacts the block and the preliminary force is applied.

C.1.7 Preliminary Indentation

When a flat anvil is used, it is recommended that at least one preliminary Rockwell test be performed at any location on the test surface of the SRM. The preliminary test will help seat the SRM block on the anvil. The measured hardness value of the preliminary test should be ignored. The user is cautioned not to make the preliminary indentation such that it contacts a previous indentation, or the engraved circle, or NIST logo. Doing so may damage the indenter. A preliminary indentation is not necessary when using a spot anvil.

C.1.8 Testing Cycle

The SRMs have been standardized by performing Rockwell tests using a specific testing cycle. The Rockwell testing cycle may be characterized by specifying testing cycle parameters that have been determined to have a significant influence on the measurement results. To minimize the uncertainty in the hardness measurement, a testing cycle should be used that replicates, as closely as possible, the SRM standardizing testing cycle parameters as identified in the certificate accompanying the test block SRM. Deviations from the SRM testing cycle in dwell times or force application rate may result in measured hardness values that are shifted from measurements made using the SRM standardizing testing cycle.

C.1.9 Indentation Spacing

The user must recognize that a Rockwell hardness measurement may be influenced by a nearby previously made indentation. The certificate accompanying the test block SRM provides guidance for acceptable spacing of indentations. In addition to avoiding making measurements too close to previously made indents, no Rockwell measurement should be made within 1 mm of the engraved circle or the NIST logo.

C.2 Calculation of Certified Values for Arbitrary Locations

A hardness measurement is destructive in that a specific location on a hardness block can be measured only once. Because hardness blocks are not uniform, NIST can only predict the hardness at untested locations available for customer measurement. The certificate that accompanies NIST Rockwell hardness SRM test blocks provides such predictions for eleven specific locations on the test block. This section provides the formulas used by NIST to make these predictions. With these formulas, the user is not limited only to the eleven locations listed in the SRM certificate but will be able to calculate a certified hardness value for any location on the block. These formulas can also be used for calculating various averages of the hardness values that are obtained by averaging over two or more arbitrary locations.

Thinking of hardness as a function of location, we denote any untested location on the block as $s_i = (x_i, y_i)$ and the corresponding hardness at each location as $H(s_i)$. Figure C.1 shows the coordinate system for (x_i, y_i). Let $\overline{H}$ be the average of the hardnesses for the n locations $s_1, \ldots, s_n$. This average is given by

(1) $$\overline{H} = \frac{1}{n}\sum_{k=1}^{n} H(\mathbf{s}_k)$$

By using the methods and formulas presented in this annex, a certified hardness value can be calculated which predicts this average hardness for any number of arbitrary locations on an SRM block. This predicted average hardness is denoted as $\hat{\bar{H}}$. As an example, consider the eleven locations (A through K) on the block illustrated in Figure C.1. A hypothetical certified average hardness value for a grouping of six of these eleven locations (B, D, F, G, I, J) is given in Table C.1. When a prediction of only one location is desired, then $n = 1$, and $\hat{\bar{H}}$ represents the hardness at a single location, (i.e., $\hat{\bar{H}} = \hat{H}(s_1)$). As an example, for point A, we have $s_1 = (0, 23)$. The certified value, $\hat{\bar{H}} = \hat{H}(s_1)$, for point A is given in Table C.2.

Table C.1.

Hypothetical certified hardness values for the average of six specific test block locations as illustrated in Figure C.1

Locations	Average Hardness Value
B, D, F, G, I, J	64.58 ± 0.16 HRC

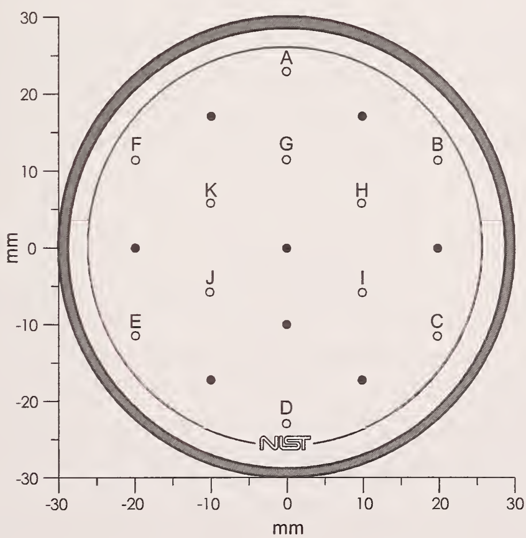


Figure C.1.

Test block surface illustrating the locations (letters A through K) of certified hardness values given in Table C.2.

Table C.2.

Hypothetical certified hardness values for specific test block locations. The x - y coordinate system is such that location x = 0, y = 0 is at the block center (NIST indentation 4), and oriented with the NIST logo at the bottom of the block as illustrated in Figure C.1

Location	x (mm)	y (mm)	Hardness
A	0	23	64.64 ± 0.17 HRC
B	20	12	64.55 ± 0. 17 HRC
C	20	-12	64.50 ± 0. 17 HRC
D	0	-23	64.57 ± 0. 17 HRC
E	-20	-12	64.62 ± 0. 17 HRC
F	-20	12	64.63 ± 0. 17 HRC
G	0	12	64.61 ± 0. 17 HRC
H	10	0	64.55 ± 0. 17 HRC
I	10	-6	64.51 ± 0. 17 HRC
J	-10	-6	64.60 ± 0. 17 HRC
K	-10	6	64.61 ± 0. 17 HRC

By analyzing the hardness profile of the set of test blocks used for the SRMs, NIST determined that the hardness is non-uniform and varies smoothly across the surface of the block. This means that, in general, the nearer two measurements are made to each other (limited to minimum spacing considerations), the closer the hardness values will be. The following method for the prediction of $\hat{\bar{H}}$ is based on modeling hardness across the surface of a block as a smooth random function described by a semivariogram. The semivariogram can be thought of as a mathematical model that describes the relationship of the spacing between any two locations on the test block and the measured hardness difference of the two locations. In statistical terms, this semivariogram gives you one half of the variance of the hardness difference between any two locations on the test block. Thus, the square root of twice the semivariogram gives the standard deviation of this difference.

For the SRM hardness block, the semivariogram is given by a simple function of Euclidean distance. Consider two points s_i and s_j separated by the distance

(2) $$d = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \,,$$

which is given in millimeters. The semivariogram is given by

$$(3) \quad \gamma(s_i - s_j) = \begin{cases} 0 & \text{if } d = 0 \\ c_o + c_e \left[1 - \exp\left(-d / a_e \right) \right] & \text{if } d \neq 0 \end{cases}$$

where c_0, c_e, and $1/a_e$ are given in Table C.3.

Table C.3.

Hypothetical semivariogram coefficients that describe test block nonuniformity and repeatability

Coefficients	Values
c_o	0.0001
c_e	0.0025
$1/a_e$	0.0505

In addition to the semivariogram, calculation of certified values requires the seven hardness readings obtained by NIST. These readings are given in Table C.4 and illustrated in Figure C.2. The location designated as "Seat" indicates a seating indentation that was made prior to making the seven calibration indentations. The locations of the NIST hardness readings are denoted by $s_{N1},\ldots,s_{N7}$, and the readings themselves by $H(s_{N1}),\ldots,H(s_{N7})$.

Table C.4.

Hypothetical NIST hardness readings for specific test block locations

Location	X	Y	Hardness Value (HRC)	Symbol
1	-10	17	64.676	$H(s_{N1})$
2	20	0	64.455	$H(s_{N2})$
4	-10	-17	64.636	$H(s_{N4})$
4	0	0	64.527	$H(s_{N4})$
5	10	17	64.642	$H(s_{N5})$
6	10	-17	64.508	$H(s_{N6})$
7	-20	0	64.621	$H(s_{N7})$

A complete certified value involves computation of three quantities: (1) the average hardness value itself, denoted by $\hat{\bar{H}}$; (2) the standard uncertainty for test block uniformity and repeatability, σ_1; and (3) the combined standard uncertainty denoted by u_c. The first quantity, the average hardness prediction $\hat{\bar{H}}$, is calculated as a linear combination of the NIST readings given by

(4) $$\hat{\bar{H}} = \sum_{i=1}^{7} \lambda_i H(s_{Ni}) .$$

Figure C.2.

Test surface of the Rockwell hardness SRMs indicating the location and sequence of certification indentations.

Computation of the coefficients λ_i and σ_1 requires four steps.

The first step is inversion of the *7 x 7* matrix Γ that has as its *(i, j)-element*, the semivariogram value for the NIST indent locations s_{Ni} and s_{Nj}. We have

(5) $$\Gamma = (\gamma(s_{Ni} - s_{Nj})) .$$

Note that the diagonal elements of Γ, where $i = j$, will have a value of *zero.*

Let the elements of the inverse of Γ be denoted g_{ij} so that

(6) $$\Gamma^{-1} = (g_{ij}) .$$

The elements of matrix Γ and the inverse matrix Γ^{-1} depend only on the semivariogram for the points measured by NIST and, therefore, are constant for all prediction calculations for this test block. The calculated values for the two matrices are given in Table C.5 and Table C.6.

Table C.5.

Matrix Γ

	1	2	3	4	5	6	7
1	0.000000	0.002120	0.002120	0.001643	0.001643	0.002224	0.001643
2	0.002120	0.000000	0.002120	0.001643	0.001643	0.001643	0.002224
3	0.002120	0.002120	0.000000	0.001643	0.002224	0.001643	0.001643
4	0.001643	0.001643	0.001643	0.000000	0.001643	0.001643	0.001643
5	0.001643	0.001643	0.002224	0.001643	0.000000	0.002120	0.002120
6	0.002224	0.001643	0.001643	0.001643	0.002120	0.000000	0.002120
7	0.001643	0.002224	0.001643	0.001643	0.002120	0.002120	0.000000

Table C.6.

Inverse matrix Γ^{-1} with elements g_{ij}

	1	2	3	4	5	6	7
1	-471.1106	38.6737	38.6737	101.4127	177.7553	38.2526	177.7553
2	38.6737	-471.1106	38.6737	101.4127	177.7553	177.7553	38.2526
3	38.6737	38.6737	-471.1106	101.4127	38.2526	177.7553	177.7553
4	101.4127	101.4127	101.4127	-601.7315	101.4127	101.4127	101.4127
5	177.7553	177.7553	38.2526	101.4127	-471.1106	38.6737	38.6737
6	38.2526	177.7553	177.7553	101.4127	38.6737	-471.1106	38.6737
7	177.7553	38.2526	177.7553	101.4127	38.6737	38.6737	-471.1106

The second step is computation of the *7* elements, $\bar{\gamma}_i$, $(i = 1,\ldots,7)$, which are given by

(7)
$$\bar{\gamma}_i = \frac{1}{n}\sum_{k=1}^{n}\gamma(s_k - s_{Ni})$$

where *n* is the number of user chosen locations to average. Note that this computation involves both the locations of the NIST readings and the locations for which a certified average (or single value) is desired.

The third step is computation of three quadratic forms,

(8)
$$Q_{22} = \sum_{i=1}^{7}\sum_{j=1}^{7}\bar{\gamma}_i\, g_{ij}\,\bar{\gamma}_j$$

(9) $$Q_{12} = \sum_{i=1}^{7}\sum_{j=1}^{7} g_{ij}\bar{\gamma}_j$$

(10) $$Q_{11} = \sum_{i=1}^{7}\sum_{j=1}^{7} g_{ij} \ .$$

The final step is computation of the seven coefficients $\lambda_i, (i = 1,\dots,7)$, and σ_1, the uncertainty due to block non-uniformity and lack of measurement repeatability,

(11) $$\lambda_i = \sum_{j=1}^{7} g_{ij}\bar{\gamma}_j + \frac{(1-Q_{12})}{Q_{11}}\sum_{j=1}^{7} g_{ij},$$

(12) $$\sigma_1 = \sqrt{Q_{22} - \frac{(Q_{12}-1)^2}{Q_{11}} - \frac{1}{n^2}\sum_{k=1}^{n}\sum_{m=1}^{n}\gamma(s_k - s_m)} \ .$$

The combined standard uncertainty, u_c, is obtained by combining σ_1 with the uncertainties σ_2, σ_3, and σ_4 from the other sources listed in the SRM certificate. Hypothetical values for σ_2, σ_3, and σ_4 are given in Table C.7.

Table C.7.

Sources of uncertainty for the certified average HRC hardness value with hypothetical values to be used in the examples

	Uncertainty Source	Standard Uncertainty
σ_1	Test Block Uniformity & Repeatability	
σ_2	Day to Day Variation	± 0.02 HRC
σ_3	NIST Standardizing Tester	± 0.02 HRC
σ_4	NIST Standardizing Indenter	± 0.07 HRC

The formula for the combined standard uncertainties is given by

(13) $$u_c = \sqrt{\sigma_1^2 + \sigma_2^2 + \sigma_3^2 + \sigma_4^2} \ .$$

The formula for the expanded uncertainty is given by

(14) $$U = ku_c ,$$

where $k = 2$.

The certified hardness values are reported as

(15) $$\hat{\bar{H}} \pm ku_c .$$

C.2.1 Examples

As an aid to the user, the following two examples are provided to illustrate how to use the procedures outlined above to calculate certified hardness values. In the first example, the certified hardness value and uncertainty for a single location is calculated. The second example calculates the certified value of the average hardness of six locations as well as the uncertainty in the average value. In both cases, the examples are based on an hypothetical SRM test block for which seven hypothetical NIST calibration values are given in Table C.4. Hypothetical semivariogram coefficients c_0, c_e, and $1/a_e$ used in both examples are given in Table C.3.

EXAMPLE 1 – Certified Hardness of a Single Location

This example illustrates the steps required to calculate the certified values of the hardness and uncertainty for a single location designated as "A" on the test surface of this SRM. The location of "A" is defined in Table C.2 and Figure C.1. The two values to be calculated are the certified hardness value $\hat{\bar{H}}$ and the uncertainty σ_1 to block non-uniformity and lack of measurement repeatability. The symbol $\hat{\bar{H}}$ is used to represent the certified value of the average hardness of multiple locations. Since $\hat{\bar{H}}$ represents the hardness at a single location in this example, then $\hat{\bar{H}} = \hat{H}(s_1)$ where s_1 is the designation for location A.

Determination of $\hat{\bar{H}}$:

The formula for calculating the certified hardness value is given by Equation 4 above as

$$\hat{\bar{H}} = \hat{H}(\mathbf{s}_1) = \sum_{i=1}^{7} \lambda_i H(\mathbf{s}_{Ni}) \ .$$

The seven NIST measured hardness values, denoted as $H(s_{Ni})$ $(i = 1,\ldots,7)$ in this formula, are provided above in Table C.4. Therefore, the only quantities that need to be determined are the seven coefficients $\lambda_i, (i = 1,\ldots,7)$. The formula for calculating these values is given by Equation 11 as

$$\lambda_i = \sum_{j=1}^{7} g_{ij} \bar{\gamma}_j + \frac{(1-Q_{12})}{Q_{11}} \sum_{j=1}^{7} g_{ij} \ .$$

Determination of U:

The formula for calculating the certified uncertainty is

$$U = ku_c \text{, where } k = 2 \ .$$

The combined standard uncertainty, u_c, is obtained by combining the sources of uncertainty σ_1, σ_2, σ_3, and σ_4 listed in Table C.7 above. The formula for combining, u_c, is given by Equation 13. The uncertainties σ_2, σ_3, and σ_4 remain constant for the computation of hardness for all locations of this SRM. Thus, in order to determine U, only the uncertainty σ_1, due to block non-uniformity and lack of measurement repeatability, must be calculated. The formula for σ_1 is given in Equation 12 as

$$\sigma_1 = \sqrt{Q_{22} - \frac{(Q_{12} - 1)^2}{Q_{11}} - \frac{1}{n^2} \sum_{k=1}^{n} \sum_{m=1}^{n} \gamma(s_k - s_m)} \ .$$

Since the certified hardness of only one location is to be determined, then $n = 1$ and the above equation simplifies to

$$\sigma_1 = \sqrt{Q_{22} - \frac{(Q_{12} - 1)^2}{Q_{11}}} \ .$$

Calculation Steps: From these formulas, it can be seen that the determination of the certified hardness and uncertainty values requires the calculation of only a one dimensional array having elements $\bar{\gamma}_i$, $(i = 1,\ldots,7)$, and a two dimensional array having elements g_{ij}, $(i = 1,\ldots,7)$ and $(j = 1,\ldots,7)$. For this example, the array elements g_{ij} are provided to the user in Table C.6. The quantities Q_{11}, Q_{12}, and Q_{22} are summations of the products of the elements of these arrays.

Note: If desired, the values Q_{11}, Q_{12}, Q_{22}, and λ_i may be calculated by matrix multiplication. The user may find it convenient to perform these calculations using commercial spreadsheet software. Today's spreadsheet programs typically provide routines or functions for performing matrix multiplication. This can simplify the task of carrying out these calculations. Equivalent representations of these formulas are given in C.2.2.

Using the formulas for $\hat{\bar{H}}$ and U above, the certified values are calculated as follows.

Step 1: Determine the location coordinates

To begin, the user must first determine the coordinates of the location where the hardness is to be determined. The *x-y* coordinate system that must be used is as shown in Figure C.1 with location (*0, 0*) at the block center (NIST indentation 4) and with the block rotated such that the NIST logo is positioned at the bottom. All measurements must be in mm. For location A, Table C.2 gives the location coordinates as $x_1 = 0\ mm$, and $y_1 = 23\ mm$. Thus we have

$$s_1 = (0,23) .$$

Step 2: Determine the array with elements $\bar{\gamma}_i$

As shown above, the array elements $\bar{\gamma}_i$, $(i = 1,\ldots,7)$, are used in the calculation of both the certified hardness value $\hat{\bar{H}}$ and the uncertainty U. The formula for calculating the values $\bar{\gamma}_i$ is given by Equation 7 as

$$\bar{\gamma}_i = \frac{1}{n}\sum_{k=1}^{n}\gamma(s_k - s_{Ni}) .$$

Since $n = 1$, this formula simplifies to the semivariogram

$$\bar{\gamma}_i = \gamma(s_1 - s_{Ni}) .$$

Determination of the elements $\gamma(s_1 - s_{Ni})$, $(i = 1,\ldots,7)$, is accomplished by using a form of Equations 2 and 3. Equation 2 becomes

$$d_i = \sqrt{(x_1 - x_i)^2 + (y_1 - y_i)^2} ,$$

where x_1 and y_1 are the location coordinates, in mm, for location A on the test surface of the SRM block. The values x_1 and y_1, $(i = 1,\ldots,7)$, are the location coordinates of the seven NIST measurement indentations in numerical order, as given above in Table C.4, and shown in Figure C.2. Thus,

$$d_i = \sqrt{(0 - x_i)^2 + (23 - y_i)^2} \ .$$

By substituting the seven NIST indentation location coordinates into this formula,

$$d_i = \begin{bmatrix} 11.50 \\ 30.48 \\ 41.54 \\ 23.00 \\ 11.50 \\ 41.54 \\ 30.48 \end{bmatrix} \quad (i = 1,\ldots,7) \ .$$

Since $d_i \neq 0$, Equation 3 becomes

$$\gamma(s_1 - s_i) = c_0 + c_e \left[1 - \exp\left(-d_i / a_e\right)\right] ,$$

where c_0, c_e, and $1/a_e$ are given in Table C.3 above. By substituting the values for d_i into the formula, the values for the seven $\bar{\gamma}_i$ elements are found to be

$$\bar{\gamma}_i = \gamma(s_1 - s_i) = \begin{bmatrix} 0.001154 \\ 0.002019 \\ 0.002249 \\ 0.001772 \\ 0.001154 \\ 0.002249 \\ 0.002019 \end{bmatrix} \quad (i = 1,\ldots,7) \cdot$$

Step 3: Determine $Q_{22}, Q_{12}, and\ Q_{11}$

The calculation of $Q_{22}, Q_{12}, and\ Q_{11}$ requires the values for the array elements $\bar{\gamma}_i$, $(i = 1,\ldots,7)$, which were calculated above in Step 2, and the elements g_{ij}, $(i = 1,\ldots,7\ and\ j = 1,\ldots,7)$, which are given in Table C.6. Substituting the values for $\bar{\gamma}_i$ and g_{ij} into the formulas yields

$$Q_{22} = \sum_{i=1}^{7}\sum_{j=1}^{7}\bar{\gamma}_i\, g_{ij}\, \bar{\gamma}_j = 0.001477,$$

$$Q_{12} = \sum_{i=1}^{7}\sum_{j=1}^{7} g_{ij}\, \bar{\gamma}_j = 1.111513, \text{ and}$$

$$Q_{11} = \sum_{i=1}^{7}\sum_{j=1}^{7} g_{ij} = 615.2209\ .$$

Step 4: Determine λ_i

The coefficients λ_i, $(i = 1,\ldots,7)$, are the last quantities that are needed for the calculation of $\hat{\bar{H}} = \hat{H}(s_1)$. By substituting the values for $\bar{\gamma}_i$, g_{ij}, Q_{12}, and Q_{11} into the formula yields

$$\lambda_i = \sum_{j=1}^{7} g_{ij}\,\bar{\gamma}_j + \frac{(1-Q_{12})}{Q_{11}}\sum_{j=1}^{7} g_{ij} = \begin{bmatrix} 0.432567 \\ 0.024021 \\ 0.027304 \\ 0.032216 \\ 0.432567 \\ 0.027304 \\ 0.024021 \end{bmatrix} \quad (i = 1,\ldots,7)\ .$$

Step 5: Determine the certified hardness value $\hat{H}(s_1)$

Substituting the values for the λ_i coefficients and the NIST hardness values $H(s_{Ni})$, $(i = 1,\ldots,7)$, yields

$$\hat{\bar{H}} = \hat{H}(s_1) = \sum_{i=1}^{7}\lambda_i H(s_{Ni}) = 64.644\ HRC.$$

Step 6: Determine the uncertainty

Now that the certified hardness value is calculated, the associated uncertainty in the certified value, $U = ku_c$, must be determined. To accomplish this, the only additional calculation needed is to determine σ_1, the uncertainty due to block non-uniformity and lack of measurement repeatability. Substituting the values for Q_{22}, Q_{12}, and Q_{11} into the formula yields

$$\sigma_1 = \sqrt{Q_{22} - \frac{(Q_{12} - 1)^2}{Q_{11}}} = 0.038165 \,.$$

Step 7: Determine the combined standard uncertainty u_c

Substituting the values for σ_1, σ_2, σ_3, and σ_4 into Equation 13 yields

$$u_c = \sqrt{\sigma_1^2 + \sigma_2^2 + \sigma_3^2 + \sigma_4^2} = \sqrt{(0.04)^2 + (0.02)^2 + (0.02)^2 + (0.07)^2} = 0.085.$$

Step 8: Determine the uncertainty $U = ku_c$

Substituting the values for u_c and $k = 2$ into equation 14 yields

$$U = ku_c = 0.17 \,.$$

Step 9: Determine the complete certified hardness value

Combining the calculated hardness value and the uncertainty yields the certified hardness at location A as

64.64 ± 0.17 HRC.

EXAMPLE 2 – Certified Hardness of the Average of Six Locations

This second example expands on Example 1 above by calculating the certified *average* of the hardness at multiple locations on the test surface of a hypothetical SRM. For this example, the average hardness and the uncertainty in this value will be calculated for a grouping of six locations (B, D, F, G, I, J) as defined above in Table C.2 and Figure C.1. As in Example 1, the two values to be calculated are the certified hardness value $\hat{\bar{H}}$ and the uncertainty U.

Determination of $\hat{\bar{H}}$ **:**

The formula for calculating the certified hardness value is given by Equation 4 as

$$\hat{\bar{H}} = \hat{H}(s_1) = \sum_{i=1}^{7} \lambda_i H(s_{Ni}) \ .$$

The seven NIST measured hardness values, denoted as $H(s_{Ni})$ $(i = 1,\ldots,7)$ in this formula, are given in Table C.4. Therefore, the only quantities that need to be determined are the seven coefficients $\lambda_i, (i = 1,\ldots,7)$. The formula for calculating these values is given by Equation 11 as

$$\lambda_i = \sum_{j=1}^{7} g_{ij} \bar{\gamma}_j + \frac{(1 - Q_{12})}{Q_{11}} \sum_{j=1}^{7} g_{ij} \ .$$

Determination of U:

The formula for calculating the certified uncertainty is

$$U = ku_c, \text{ where } k = 2 \cdot$$

The combined standard uncertainty, u_c, is obtained by combining the sources of uncertainty σ_1, σ_2, σ_3, and σ_4 listed in Table C.7 above. The formula for combining u_c is given by Equation 13. The uncertainties σ_2, σ_3, and σ_4 remain constant for the computation of hardness for all locations of this SRM. Thus, in order to determine, only the uncertainty σ_1, due to block non-uniformity and lack of measurement repeatability, must be calculated. The formula for σ_1 is given in Equation 12 as

$$\sigma_1 = \sqrt{Q_{22} - \frac{(Q_{12} - 1)^2}{Q_{11}} - \frac{1}{n^2} \sum_{k=1}^{n} \sum_{m=1}^{n} \gamma(s_k - s_m)} \ .$$

Calculation Steps: From these formulas, it can be seen that the determination of the certified hardness and uncertainty values requires the calculation of a one dimensional array having elements $\bar{\gamma}_i$, $(i = 1,\ldots,7)$, a two dimensional array having elements $\gamma(s_k - s_m)$, $(k = 1,\ldots,6$ and $m = 1,\ldots,6)$, and a two dimensional array having elements g_{ij}, $(i = 1,\ldots,7$ and $j = 1,\ldots,7)$. For this hypothetical SRM, the array elements g_{ij} are provided to the user in Table C.7. The quantities Q_{11}, Q_{12}, and Q_{22} are summations of the products of the elements of these arrays, as defined in Equations 8, 9, and 10.

If desired, the values Q_{11}, Q_{12}, Q_{22}, and λ_i may be calculated by matrix multiplication. The user may find it convenient to perform these calculations with the assistance of commercial spreadsheet software. Today's spreadsheet programs typically provide routines or functions for performing matrix multiplication. This can simplify the task of carrying out these calculations. Equivalent representations of these formulas are given in C.2.2.

Using the formulas for $\hat{\bar{H}}$ and U above, the certified values are calculated as follows.

Step 1: Determine the location coordinates

To begin, the user must first determine the coordinates of the location where the average hardness is to be determined. The *x-y* coordinate system that must be used is as shown in Figure C.1 with location (*0, 0*) at the block center (NIST indentation 4) and with the block rotated such that the NIST logo is positioned at the bottom. All measurements must be in mm. The *x*-y coordinates of locations B, D, F, G, I, and J are given in Table C.8.

Table C.8.

The coordinates for the locations used in the calculations of Example 2

Location	X (mm)	Y (mm)	Symbol
B	20	12	s_1
D	0	-23	s_2
F	-20	12	s_3
G	0	12	s_4
I	10	-6	s_5
J	-10	-6	s_6

Step 2: Determine the array with elements $\bar{\gamma}_i$

As shown above, the array elements $\bar{\gamma}_i$, $(i = 1,\ldots,7)$, are used in the calculation of both the certified hardness value $\hat{\bar{H}}$ and the uncertainty U. The formula for calculation of the values $\bar{\gamma}_i$ is given by Equation 7 as

$$\bar{\gamma}_i = \frac{1}{n}\sum_{k=1}^{n} \gamma(s_k - s_{Ni}).$$

Determination of the elements $\gamma(s_k - s_{Ni})$, $(k = 1,\ldots,7)$, for $i = 1,\ldots,n$, where $n = 6$, is accomplished by using a form of Equations 2 and 3. Equation 4 becomes

$$d_{kNi} = \sqrt{(x_k - x_{Ni})^2 + (y_k - y_{Ni})^2},$$

where x_k and y_k $(k = 1,\ldots,6)$ are the location coordinates in mm for the six locations B, D, F, G, I, and J on the test surface of the SRM block. The values x_{Ni} and y_{Ni}, $(i = 1,\ldots,7)$, are the location coordinates of the seven NIST measurement indentations in numerical order, as given in Table C.4, and shown in Figure C.2. Thus, the values of d_{kNi} will be a 7×6 two dimensional array

$$(k = 1,\ldots,6)$$

$$d_{kNi} = \begin{bmatrix} 30.47 & 41.54 & 11.33 & 11.33 & 30.72 & 23.32 \\ 12.00 & 30.48 & 41.76 & 23.32 & 11.66 & 30.59 \\ 41.95 & 11.50 & 30.98 & 30.98 & 22.98 & 11.32 \\ 23.32 & 23.00 & 23.32 & 12.00 & 11.66 & 11.66 \\ 11.33 & 41.54 & 30.47 & 11.33 & 23.32 & 30.72 \\ 30.98 & 11.50 & 41.95 & 30.98 & 11.32 & 22.98 \\ 41.76 & 30.48 & 12.00 & 23.32 & 30.59 & 11.66 \end{bmatrix} (i = 1,\ldots,7).$$

Similarly, Equation 3 becomes

$$\gamma(\mathbf{s}_k - \mathbf{s}_{Ni}) = \begin{cases} 0 & \text{if } d_{kNi} = 0 \\ c_o + c_e \left[1 - \exp\left(-d_{kNi}/a_e\right)\right] & \text{if } d_{kNi} \neq 0 \end{cases},$$

where c_0, c_e, and $1/a_e$ are given in Table C.3 above. By substituting the values for d_{kNi} into the formula, the values of $\gamma(\mathbf{s}_k - \mathbf{s}_{Ni})$ are found to be

$$(k = 1, \ldots, 6)$$

$$\gamma(\mathbf{s}_k - \mathbf{s}_{Ni}) = \begin{bmatrix} 0.002018 & 0.002249 & 0.001142 & 0.001142 & 0.002025 & 0.001784 \\ 0.001189 & 0.002019 & 0.002252 & 0.001784 & 0.001166 & 0.002022 \\ 0.002255 & 0.001154 & 0.002032 & 0.002032 & 0.001771 & 0.001141 \\ 0.001784 & 0.001772 & 0.001784 & 0.001189 & 0.001166 & 0.001166 \\ 0.001142 & 0.002249 & 0.002018 & 0.001142 & 0.001784 & 0.002025 \\ 0.002032 & 0.001154 & 0.002255 & 0.002032 & 0.001141 & 0.001771 \\ 0.002252 & 0.002019 & 0.001189 & 0.001784 & 0.002022 & 0.001166 \end{bmatrix} (i = 1, \ldots, 7).$$

Finally, each of the seven rows of $\gamma(\mathbf{s}_k - \mathbf{s}_{Ni})$ above must be summed and divided by $n = 6$ to calculate the seven elements of $\bar{\gamma}_i$. Thus,

$$\bar{\gamma}_i = \frac{1}{n}\sum_{k=1}^{n} \gamma(\mathbf{s}_k - \mathbf{s}_{Ni}) = \begin{bmatrix} 0.001727 \\ 0.001739 \\ 0.001731 \\ 0.001477 \\ 0.001727 \\ 0.001731 \\ 0.001739 \end{bmatrix} (i = 1, \ldots, 7).$$

Step 3: Determine Q_{22}, Q_{12}, and Q_{11}

The calculation of Q_{22}, Q_{12}, and Q_{11} requires the values for the array elements $\bar{\gamma}_i$, $(i = 1,\ldots,7)$, which were calculated above in Step 2, and the elements g_{ij}, $(i = 1,\ldots,7$ and $j = 1,\ldots,7)$, which are given in Table C.6. Substituting the values for $\bar{\gamma}_i$ and g_{ij} into the formulas yields

$$Q_{22} = \sum_{i=1}^{7}\sum_{j=1}^{7}\bar{\gamma}_i\, g_{ij}\,\bar{\gamma}_j = 0.0018,$$

$$Q_{12} = \sum_{i=1}^{7}\sum_{j=1}^{7} g_{ij}\,\bar{\gamma}_j = 1.063846 \text{, and}$$

$$Q_{11} = \sum_{i=1}^{7}\sum_{j=1}^{7} g_{ij} = 615.2209\,.$$

Step 4: Determine λ_i

The coefficients λ_i, $(i = 1,\ldots,7)$, are the last quantities that are needed for the calculation of $\hat{\bar{H}}$. By substituting the values for $\bar{\gamma}_i$, g_{ij}, Q_{12}, and Q_{11} into the formula yields

$$\lambda_i = \sum_{j=1}^{7} g_{ij}\,\bar{\gamma}_j + \frac{(1-Q_{12})}{Q_{11}}\sum_{j=1}^{7} g_{ij} = \begin{bmatrix} 0.142140 \\ 0.135009 \\ 0.140579 \\ 0.164544 \\ 0.142140 \\ 0.140579 \\ 0.135009 \end{bmatrix} \quad (i = 1,\ldots,7)\,.$$

Step 5: Determine the certified hardness value $\hat{H}(s_1)$

Substituting the values for the λ_i coefficients and the NIST hardness values $H(s_{Ni})$, $(i = 1,\ldots,7)$ yields

$$\hat{\bar{H}} = \sum_{i=1}^{7}\lambda_i H(s_{Ni}) = 64.580 \text{ HRC}\,.$$

Step 6: Determine the uncertainty σ_1

Now that the certified hardness value is calculated, the associated uncertainty in the certified value, $U = ku_c$, must be determined. To accomplish this, the only additional calculation needed is to determine σ_1, the uncertainty due to block non-uniformity, and lack of measurement repeatability. The formula for calculating σ_1 is given in Equation 12 as

$$\sigma_1 = \sqrt{Q_{22} - \frac{(Q_{12} - 1)^2}{Q_{11}} - \frac{1}{n^2}\sum_{k=1}^{n}\sum_{m=1}^{n}\gamma(s_k - s_m)}\ .$$

Determination of the elements $\gamma(s_k - s_m)$, $(k = 1,\ldots,n$ and $m = 1,\ldots,n)$, where $n = 6$, is accomplished by using a form of Equations 2 and 3. Equation 2 becomes

$$d_{km} = \sqrt{(x_k - x_m)^2 + (y_k - y_m)^2}\ ,$$

where (x_k, y_k), $(k = 1,\ldots,6)$ and (x_m, y_m), $(m = 1,\ldots,6)$ are the location coordinates in mm for two of the six points of interest on the test surface of the SRM block, in this case, the six locations B, D, F, G, I, and J. A value of d_{km} must be calculated for all pairing combinations of the six locations. Thus, the values of d_{km} will be a 6×6 two dimensional array

$$d_{km} = \overset{(k = 1,\ldots,6)}{\begin{bmatrix} 0.00 & 40.31 & 40.00 & 20.00 & 20.59 & 34.99 \\ 40.31 & 0.00 & 40.31 & 35.00 & 19.72 & 19.72 \\ 40.00 & 40.31 & 0.00 & 20.00 & 34.99 & 20.59 \\ 20.00 & 35.00 & 20.00 & 0.00 & 20.59 & 20.59 \\ 20.59 & 19.72 & 34.99 & 20.59 & 0.00 & 20.00 \\ 34.99 & 19.72 & 20.59 & 20.59 & 20.00 & 0.00 \end{bmatrix}}\ (m = 1,\ldots,6)\ .$$

Similarly, Equation 3 becomes

$$\gamma(s_k - s_m) = \begin{cases} 0 & \text{if } d_{km} = 0 \\ c_0 + c_e \left[1 - \exp\left(-d_{km}/a_e\right)\right] & \text{if } d_{km} \neq 0 \end{cases},$$

where c_0, c_e, and $1/a_e$ are given in Table C.3 above. By substituting the values for d_{km} into the formula, the values of $\gamma(s_k - s_m)$ are found to be

$$(k = 1,\ldots,6)$$

$$\gamma(s_k - s_m) = \begin{bmatrix} 0.000000 & 0.002229 & 0.002224 & 0.001643 & 0.001670 & 0.002128 \\ 0.002229 & 0.000000 & 0.002229 & 0.002128 & 0.001631 & 0.001631 \\ 0.002224 & 0.002229 & 0.000000 & 0.001643 & 0.002128 & 0.001670 \\ 0.001643 & 0.002128 & 0.001643 & 0.000000 & 0.001670 & 0.001670 \\ 0.001670 & 0.001631 & 0.002128 & 0.001670 & 0.000000 & 0.001643 \\ 0.002128 & 0.001631 & 0.001670 & 0.001670 & 0.001643 & 0.000000 \end{bmatrix} (m = 1,\ldots,6).$$

Finally, all of the elements of $\gamma(s_k - s_m)$ above must be summed and divided by $n = 36$. Thus,

$$\frac{1}{n^2}\sum_{k=1}^{n}\sum_{m=1}^{n}\gamma(s_k - s_m) = 0.001552.$$

Substituting this value and the values for Q_{22}, Q_{12}, and Q_{11} into the formula for σ_1 above yields

$$\sigma_1 = \sqrt{Q_{22} - \frac{(Q_{12} - 1)^2}{Q_{11}} - \frac{1}{n^2}\sum_{k=1}^{n}\sum_{m=1}^{n}\gamma(s_k - s_m)} = 0.015543.$$

Step 7: Determine the combined standard uncertainty u_c

Substituting the values for σ_1, σ_2, σ_3, and σ_4 into Equation 13 yields

$$u_c = \sqrt{\sigma_1^2 + \sigma_2^2 + \sigma_3^2 + \sigma_4^2} = \sqrt{(0.02)^2 + (0.02)^2 + (0.02)^2 + (0.07)^2} = 0.078.$$

Step 8: Determine the uncertainty $U = ku_c$

Substituting the values for u_c and $k = 2$ into equation 14 yields

$$U = ku_c = 0.16 \, .$$

Step 9: Determine the complete certified hardness value

Combining the calculated hardness value and the uncertainty yields the certified average value of the hardness at locations B, D, F, G, I, and J as

64.58 ± 0.16 HRC.

C.2.2 Matrix Equivalents to Formulas of Annex C

Equivalent matrix representations of Q_{11}, Q_{12}, Q_{22} and λ_i are

$$Q_{22} = \sum_{i=1}^{7}\sum_{j=1}^{7} \bar{\gamma}_i \, g_{ij} \, \bar{\gamma}_j = \gamma' \Gamma^{-1} \gamma ,$$

$$Q_{12} = \sum_{i=1}^{7}\sum_{j=1}^{7} g_{ij} \, \bar{\gamma}_j = \mathbf{1}' \Gamma^{-1} \gamma ,$$

$$Q_{11} = \sum_{i=1}^{7}\sum_{j=1}^{7} g_{ij} = \mathbf{1}' \Gamma^{-1} \mathbf{1} , \text{ and}$$

$$\lambda_i = \sum_{j=1}^{7} g_{ij} \, \bar{\gamma}_j + \frac{(1 - Q_{12})}{Q_{11}} \sum_{j=1}^{7} g_{ij} = \Gamma^{-1}\gamma + \frac{(1 - \mathbf{1}'\Gamma^{-1}\gamma)}{\mathbf{1}'\Gamma^{-1}\mathbf{1}} \left(\Gamma^{-1}\mathbf{1} \right) ,$$

where Γ^{-1} is the matrix having g_{ij} , $(i = 1,\ldots,7)$ and $(j = 1,\ldots,7)$ as its elements, and **1** is an *n* vector with 1 as elements, such that

$$\mathbf{1} = \begin{vmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \end{vmatrix} , \text{ and}$$

$$\mathbf{1}' = \begin{vmatrix} 1111111 \end{vmatrix} .$$

NIST CENTENNIAL 1901-2001

January 2001