MECHANICAL TESTING

HARDNESS TESTING

INTRODUCTION

Static indentation hardness tests such as Brinell, Rockwell, Vickers, and Knoop are frequently used methods for determining hardness. The basic concept utilized in all of these tests is that a set force is applied to an indenter in order to determine the resistance of the material to penetration. If the material is hard, a relatively small or shallow indentation will result, whereas if the material is soft, a fairly large or deep indentation will result.

These tests are often classified in one of two ways: either by the extent of the test force applied or the measurement method used. A "macro" test refers to a test where a load >1 kg is applied; similarly "micro" refers to a test where a load of ≤ 1 kg of force is applied. Additionally, some instruments are capable of conducting tests with loads as light as 0.01 g and are commonly referred to as ultralight or nanoindentation testers. Rockwell and Brinell testers fall into the macro category, whereas Knoop testers are used for microindentation tests. Vickers testers are employed for both macro and microindentation tests. The measurement methods available include a visual observation of the indentation or a depth measurement of the indentation. Rockwell and some nanoindentation testers are capable of determining the depth of the indentation, whereas Brinell, Knoop, and Vickers testers require an indentation diameter measurement. These visual measurements can be automated, as will be discussed later in this unit.

Hardness is not a fundamental property of a material, yet hardness testing is considered a useful quality-control tool. Many properties are predicted from hardness values when combined with additional information such as alloy composition. The following is a list of such properties: resistance to abrasives or wear, resistance to plastic deformation, modulus of elasticity, yield strength, ductility, and fracture toughness. Some of these properties, such as yield strength, have numerical relationships with hardness values, whereas others such as fracture toughness are based on observations of cracks surrounding the indentations. Data analysis and conversions will be discussed in greater detail later in this unit.

Other relationships have developed over time by empirical observations such as the link between machinability and hardness values. In general, 300 to 350 HB (Brinell scale) is considered to be the maximum tolerable hardness for production machining of steels. For the majority of machining operations, the optimum hardness is 180 to 200 HB. If the material is too soft—<160 HB—poor chip formation and a poor surface finish will result. The relationship between hardness and machinability, however, is not linear. Equations were developed by Janitzky (1938) and Henkin and Datsko (1963) for determining machinability if the Brinell hardness and tensile reduction of area are known.

Competitive and Related Techniques

Many techniques have been used historically to determine hardness. The tests focused on here—static indentation hardness test methods—are widely used because of the ease of use and repeatability of the technique. Rebound and ultrasonic tests are the next most common, due to portability. Several hardness techniques are listed below with an emphasis placed on either the specific applications for which these were developed or the limitations of these techniques in comparison to static indentation tests.

Rebound tests, routinely done with Scleroscope testers, consist of dropping a diamond-tipped hammer, which falls inside a glass tube under the force of its own weight from a fixed height, onto the test specimen and reading the rebound travel on a graduated scale. The advantage of such a method is that many tests can be conducted in a very short time. However, there are several limitations to consider. The column must be in an upright position, so that even if the tester is portable it must be positioned correctly. While newer testers have a digital readout, on the older models the height of the rebound had to be closely observed by the operator (Boyer et al., 1985).

In ultrasonic microhardness testing, a Vickers diamond is attached to one end of a magnetostrictive metal rod. The diamond-tipped rod is excited to its natural frequency. The resonant frequency of the rod changes as the free end of the rod is brought into contact with the surface of the test specimen. The area of contact between the indenter and the test material can be determined by the measured frequency. However, the Young's modulus of the material must be known in order to accomplish this calculation. Only a small indent is left on the surface, so the test is classified as nondestructive. The disadvantage of this is that it is difficult to confirm the exact location of the test (Meyer et al., 1985).

One of the earliest forms of hardness testing, scratch testing, goes back to Reaumur in 1722. His scale of testing consisted of a scratching bar, which increased in hardness from one end to the other. The degree of hardness was determined by the position on the bar that the metal being tested would scratch (Boyer, 1987). The next development was the Mohs scale, which has a series of ten materials used for comparison ranging from diamond with a hardness of 10, to talc with a hardness of 1 (Petty, 1971). Further developments include a file test where a series of hardened files of various Rockwell C values (HRC values; see Table 1) are used to determine the relative surface hardness. With this particular test, it is up to the operator to determine how much pressure to apply, at what speed to drag the file, and the angle at which to hold the file. A more controlled method was developed which uses a diamond tip and a set force on a mechanical arm to drag across the material. The width of the resulting

Table 1. Standard Static Indentation Hardness Tests

	ASTM	ISO
Brinell	E10	6506, 156, 726, 410
Rockwell	E18	6508, 1024, 716, 1079, 674, 1355
Vickers	E92, E384	6507, 640, 146, 409
Knoop	E384	4545, 4546, 4547

groove is examined to determine the hardness (Bierbaum, 1930). The advantage is that a single trace can be made through a microstructure and the relative hardness of the different phases and constituents can be assessed. For example, variation at grain boundaries or case-hardened surfaces would be observed. However, it is more difficult to relate this information to other properties or hardness scales.

Abrasion and wear tests are used to evaluate the life of a component under service conditions. Typically, abrasive is applied to the surface by various means such as a rotating disc, an abrasive and lubricant mixture, or steel shot impinged at a known velocity (see TRIBOLOGICAL AND WEAR TESTING). The material-removal rate is monitored to determine the hardness (Khruschov, 1957; Richardson, 1967). This method is explained in detail in TRIBOLOGICAL AND WEAR TESTING.

Instrumented indentation is one of the newer developments in hardness testing. This method takes dynamic hardness testing one step further. Not only is a loading and unloading curve developed, but also a continuous stiffness measurement is conducted throughout the time of contact between the indenter and the material. The record of the stiffness data along with the load displacement data allows the hardness and Young's modulus to be calculated as a function of depth (Oliver et al., 1992). This method is under development as are standards for the methodology.

PRINCIPLES OF THE METHOD

The basis of static indentation tests is that an indenter is forced into the surface of the material being tested for a set duration. When the force is applied to the test piece through contact with the indenter, the test piece will yield. After the force is removed, some plastic recovery in the direction opposite to the initial flow is expected, but over a smaller volume. Because the plastic recovery is not complete, biaxial residual stresses remain in planes parallel to the free surface after the force is removed. The hardness value is calculated by the amount of permanent deformation or plastic flow of the material observed relative to the test force applied. The deformation is quantified by the area or the depth of the indentation. The numerical relationship is inversely proportional, such that as the indent size or depth increases, the hardness value decreases.

The hardness is derived from two primary components: (1) a constraint factor for the test and (2) the uniaxial flow stress of the material being tested. The value of the constraint factor depends mainly on the shape of the indenter used in the hardness test. For relatively blunt indenters

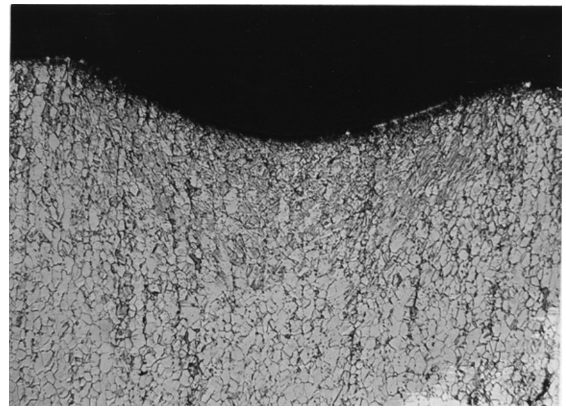

Figure 1. The cross-section of an indentation in a brass specimen demonstrates the deformation and material flow that occurs as the result of the applied force. Aqueous ferric chloride etch, 100× magnification.

such as Brinell, Vickers, and Knoop, the constraint factor is approximately three. Prandtl first explained the origin of the constraint factor (Prandtl, 1920). He compared the blunt hardness indenters to the mean stress on a two-dimensional punch required for the onset of plastic flow beneath the punch. The material beneath the punch was assumed to flow plastically in plane strain, and the material surrounding the flow pattern was considered to be rigid. Hill generalized Prandtl's approach into what is now known as the slip line field theory. Hill calculated a constraint factor very similar to Prandtl. According to these theories, the material displaced by the punch is accounted for by upward flow (Hill et al., 1947). Both calculated values closely match the empirical data. The photomicrograph in Figure 1 demonstrates the stress and flow observed in the region around an indentation.

Hardness values can be directly compared only if the same test is used, since the geometry of the indenter and force applied influence the outcome of the test. For each type of hardness test conducted, a different equation is used to convert the measured dimension, depth or diameter, to a hardness value. The Brinell hardness value is calculated by dividing the test force by the surface area of the indentation. The test parameters taken into account are the test force and ball diameter while the indentation diameter is measured. For Rockwell tests, the hardness value is determined by the depth of indentation made by a constant force impressed upon the indenter. The test parameters taken into account are the test force (major and minor load) and the indenter geometry (ball or diamond cone), while the depth of penetration between the application of the minor load and major load is measured. Vickers hardness values are calculated in the same manner as Brinell tests. The projected area, instead of the surface area, is used when computing Knoop values. The test parameters taken into account for Vickers and Knoop tests are identical and include the test force and diamond indenter geometry while the indentation diameter is measured. In addition some ultralight tests are conducted with a Berkovich indenter, which has its own unique geometry. The illustrations in Figure 2 demonstrate the indentations

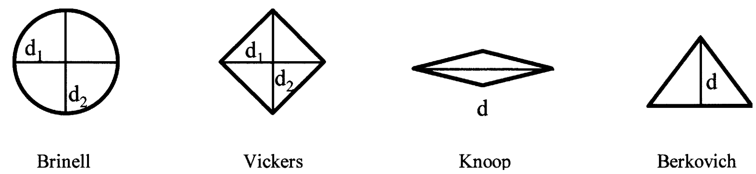

Figure 2. For the tests described in this unit, the hardness values are calculated based on the diameter of the indentation, d, which is measured differently for the different tests. Note that for the Brinell and Vickers tests, that diameter is an average of two measurements. See the Appendix for the equations in which these numbers are used.

that are measured by visual means and the dimensions of interest. The equations used to calculate the hardness values can be found in the Appendix.

The majority of hardness tests are conducted to verify that a particular processing step was done correctly. Typical processes that are evaluated include annealing, hardenability, cold working, recrystallization, surface treatments, and tempering. While an etchant could be used for visual examination of the microstructure variation, there might be other factors such as chemical composition or porosity level that would also influence the hardness value. For a known composition, the hardness associated with a particular structure will vary. For example, an alloy with a carbon content of 0.69 (wt. %) and a martensitic structure would have a hardness value of 65 HRC while an alloy with a carbon content of 0.25 and a martensitic structure would have an Rockwell C value of only 47 HRC (ASTM Standard A255, 1986).

A very common application for microindentation hardness tests is in verifying or dertermining case depth as a result of a heat-treatment process—i.e., case hardening. Case hardening may be defined as a process by which a ferrous material is hardened so that a surface layer, known as the case, becomes substantially harder than the remaining material, known as the core. The graph in Figure 3 is representative of an evaluation to determine an "effective" case depth. "Effective" case depth is the depth at which 50 Rockwell C is obtained. The "total" case depth is where hardness becomes constant. Often the visual transition is observed at a depth near the total case depth.

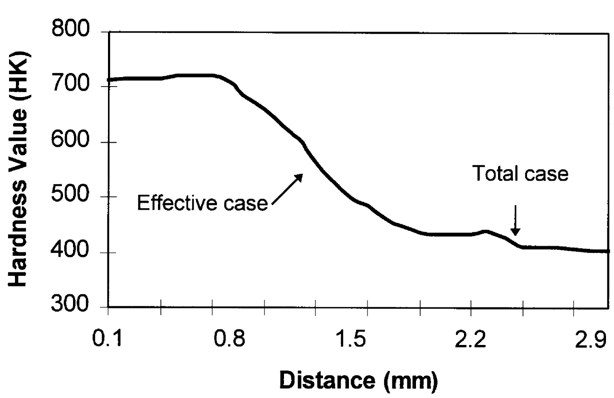

Figure 3. The effective and total case depth are noted in this typical case-depth determination graph. Even though the effective case is evaluated at 50 HRC, a Knoop (HK) test is required for this application.

PRACTICAL ASPECTS OF THE METHOD

General test methods for Brinell, Rockwell, Vickers, and Knoop tests can be found in ASTM and ISO standards. ASTM, ISO, DIN, SAE, APMI, and various other organizations also have written standards specific to certain materials, products, or processes. The standards listed in Table 1 contain information relative to the type of tester, general method, and calibration requirements.

The method described in the following paragraph has been generalized for any static indentation test. Prior to conducting the test, a specimen will typically undergo a certain level of preparation. The extent of preparation required is a function of the test force applied and is described in greater detail later in this unit (see Sample Preparation). Next, the specimen is secured through the use of a vise or an anvil. In the case of a portable tester, the tester must be secured. The main objective is to insure that the only movement observed during the course of the test is the impression of the indenter. The test force is then applied for a set duration. The measured dimension, depth, or diameter can then be used to calculate the hardness using the appropriate equation in the Appendix at the end of this unit. However, in most cases the instrument will provide a direct readout of the hardness value; otherwise a reference table containing solutions for set measurements/input values can be used.

In order to compare hardness values from one material to another, it is important for the same test conditions to be in place. Therefore, certain information needs to be provided with the hardness number. For example, 600 HBW 1/30/20 represents a Brinell hardness of 600 determined with a tungsten carbide ball 1 mm in diameter and a test force of 30 kgf (kilogram-force; 1 kgf $\equiv$ 9.80665 N) applied for 20 s. In general, the key pieces of information to provide, in addition to the hardness value, are the test method used and test force applied (if not dictated by the method). Values such as 60 HRC or 850 HV 10, where 10 represents the test force applied in kg, are typical of the notations that would be observed on blueprints.

Of the static indentation test methods discussed, each has its advantages, intended applications, and limitations. The selection criteria to consider are as follows: hardness range of material to be tested, work environment, shape and size of workpiece, surface condition and whether or not the workpiece can be modified prior to testing, heterogeneity/homogeneity of the material, number of tests to be performed, and level of automation available. A majority of the factors listed above can be correlated

Table 2. Common Applications and Nomenclature for Hardness Tests

Test	Abbreviation	Indenter	Test Load (kg)[a]	Application
Brinell	HBW	10-mm ball: tungsten carbide	3000	cast iron and steel
Brinell	HBS	10-mm ball: steel	500	copper, aluminum
Rockwell A	HRA	brale	60	very hard materials, cemented carbides
Rockwell B	HRB	$\frac{1}{16}$-in. ball	100	low-strength steel, copper alloys, aluminum alloys, malleable iron
Rockwell C	HRC	brale	150	high-strength steel, titanium, pearlitic malleable iron
Rockwell D	HRD	brale	100	high-strength steel, thin steel
Rockwell E	HRE	$\frac{1}{8}$-in. ball	100	cast iron, aluminum, and magnesium alloys
Rockwell F	HRF	$\frac{1}{16}$-in. ball	60	annealed copper alloys, thin soft metals
Superficial Rockwell T	30 T	$\frac{1}{16}$-in. ball	30	materials similar to Rockwell B, F, and G, but of thinner gauge
Superficial Rockwell N	30 N	brale	30	materials similar to Rockwell A, C, and D, but of thinner gauge
Vickers	HV	diamond	10	hard materials, ceramics, cemented carbides
Vickers	HV	diamond	0.5	all materials
Knoop	HK	diamond	0.5	all materials, case-depth determination

[a]The test load listed is specific to the application and not the only force available for the tester.

with the test force applied and the corresponding size of the indentation.

Brinell testers can be used on a wide range of materials. When test forces in the range of 500 to 3000 kgf are applied with a 10-mm-diameter ball, a diameter will be created with an indentation between 2 and 7 mm. The large impression has its advantages with heterogeneous microstructures or segregation in that it averages out the variation. The disadvantage is that it is not sensitive enough to define a gradient in hardness and not suitable for testing small parts or thin sections. The thickness of the test piece must be ten times the depth of the indent.

Rockwell testers accommodate different materials through the use of various test forces and indenters. Each combination of indenter and force is given a specific scale designation, A to Z. For example, HRC tests are conducted with a brale indenter and 150 kgf while HRB tests are conducted with a 1/16-in. ball and 100 kgf. Superficial tests are conducted at three different forces and are designated accordingly. A 15T test is accomplished with a 1/16-in. ball and 15 kgf; likewise 30T and 45T tests use the same ball indenter with 30 and 45 kgf, respectively. Rockwell tests are used to determine bulk hardness, with the exception of superficial tests. These tests are used to evaluate coatings or surface treatments such as nitriding.

The advantage of microindentation hardness tests is the ability to monitor hardness as a function of position—e.g., placing an indent in a specific microconstituent in a multiphase material, determining case depth, or determining particle hardness. The Vickers test is considered to be relatively independent of test force; this is due to the geometrically similar impressions, as made by pyramidal indenters (Vander Voort, 1984). Testers are available that accommodate a range of test forces from 50 to 0.01 kgf. This enables direct comparison of bulk and phase-specific hardness values. Knoop indenters, on the other hand, are used most often when determining case depth, due to the elongated shape of the indenter. Table 2 lists common applications for the tests discussed (Lysaght et al., 1969; Boyer, 1987).

METHOD AUTOMATION

Automation is available on different levels for the hardness test equipment. Two types of automation are typical: (1) placement of the indentations and (2) image-analysis measurement methods. The placement of indentations can be automated with the use of a motorized stage. The most common application is with microindentation hardness tests, where as many as forty indentations may be required in a series to monitor a surface treatment. Also, the smaller specimen size lends itself more readily to being placed on a stage. Automated reading of the indentations is applied in situations where the operator would typically read the indent, for example, Knoop, Vickers, and Brinell tests. The systems are based on a specialized sequence of image analysis processes. Most systems utilize a grayscale camera system with a computer system. The indentations are detected based on either the level of contrast with the matrix material or the assumption that the indent will be made up of the darker gray pixels on the screen. The accuracy of the dimensional measurements will be based on the resolution of the system as a whole, which will be determined by a combination of the optics in the measuring device/microscope and the camera.

DATA ANALYSIS AND INITIAL INTERPRETATION

The majority of modern equipment displays the hardness value directly after the measurement has been made. For Rockwell testers this means the value will be immediately displayed either on a digital readout or a dial. For a test where a visual measurement is conducted, the tester will either display the hardness value or simply the diameter value. In either case, most new testers are equipped with an RS232 interface either to automate the tester or to output the data for further analysis by the operator. For microindentation tests, one of the considerations is which data points to include and which are questionable. Due to the small size of the indentations, the values can be significantly altered by the presence of cracks, pores, and inclusions. One of the criteria to examine is if the shape of the indent is similar to that of the indenter. If a corner of the indent is missing or distorted or forms an asymmetrical indent, the value is highly questionable.

In some cases, creating cracks is actually the intent of the test (Palmquist, 1957). One case involves simply observing the force at which cracking begins. Typically, this method is employed when the material lacks enough ductility for other mechanical tests such as compression or tensile testing, or when there is a lack of material, since the hardness test requires only a small surface area. Crack-length observations are also used to calculate fracture toughness. A plot is constructed of the applied force versus the crack length, and a linear relationship is produced. The inverse of the slope in kg/mm is a measure of the fracture toughness.

Conversions from one scale to another are commonplace; however, a single conversion relationship does not hold true for all materials. Charts and equations are available for the following materials; nonaustenitic steels, nickel and high-nickel alloys, cartridge brass, austenitic stainless steel, copper, alloyed white iron, and wrought aluminum products in ASTM E140. Converted values should be used only when it is impossible to test the material under the condition specified.

Other properties of interest are tensile strength, yield strength, and hardenability (Siebert et al., 1977). Tensile-strength conversions have typically been developed around a particular material or class of materials. For example, with equations developed by Tabor (1951), a different constant is inserted for steel in comparison to copper. These findings have been duplicated in some cases and refuted in others (Taylor, 1942; Cahoon et al., 1971). Several other equations have been developed for specific hardness methods such as Brinell (Greaves et al., 1926; MacKenzie, 1946) or Vickers (Robinson et al., 1973). Likewise, yield strength conversions have been shown to vary with the material of interest (Cahoon et al., 1971; George et al., 1976). This observation was linked with the strain hardening coefficient. With aluminum alloys, the strain hardening coefficient is dependent on the strengthening mechanism, whereas for carbon steels the strain hardening coefficient varies directly with hardness.

SAMPLE PREPARATION

The degree of sample preparation required is inversely related to the depth of the indentation. For a relatively deep indentation, as is the case with Brinell tests, surface condition is less of a factor. The primary concern is that the indentation not be obscured when measuring the diameter. However, for a shallow indentation, a rough surface finish will cause a high level of variation in the readings. When conducting a superficial Rockwell test, for example, if the indenter were to slip into the valley of a groove, the depth measurement would be a combination of the impression and the slip, and the hardness value would be underestimated. Typically, for Rockwell tests, surface grinding to at least a 400-grit abrasive paper is recommended. For microindentation tests, such as Vickers and Knoop, rough polishing to a finish of 3 μm or better is recommended. With any test where the indentation diameter must be measured, the amount of deformation or scratches on the surface must not interfere with the operator's ability to determine the diameter. The surface finish requirements tend to be more stringent when automation is employed for the visual measurements.

SPECIMEN MODIFICATION

As a result of the material being forced aside by the indenter to make an impression in the specimen, the material surrounding the impression is disturbed and possibly work-hardened. For this reason, a minimum spacing requirement between indentations can be found for each type of hardness test in a corresponding standard. The spacing is specified in terms of indentation diameters, rather than units such as micrometers, to account for the greater amount of cold working that often occurs in soft materials that produce larger indentations. If indentations are too closely spaced, the hardness values can become erratic. For example, when a porous specimen is examined, the area around the indent is compressed as shown in Figure 4. Another test conducted in the compressed region would result in a higher hardness value. However, it is also possible for values to decrease, since, on contact with an existing indentation, the indenter may actually have less material to force aside and the result may be larger or deeper indentation.

Typically, loads are recommended that will result in an indent of sufficient size to be accurately measured, while

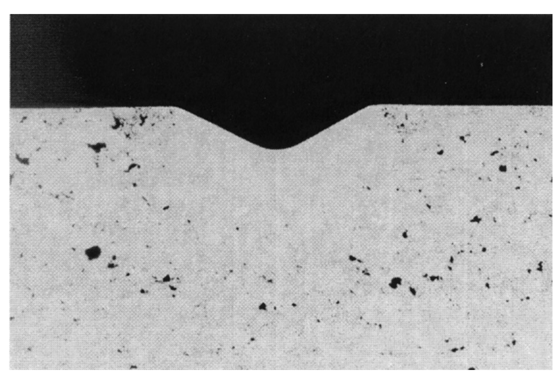

Figure 4. The cross-section of an indentation in a porous specimen demonstrating the compression of the porosity by the applied force (35× magnification).

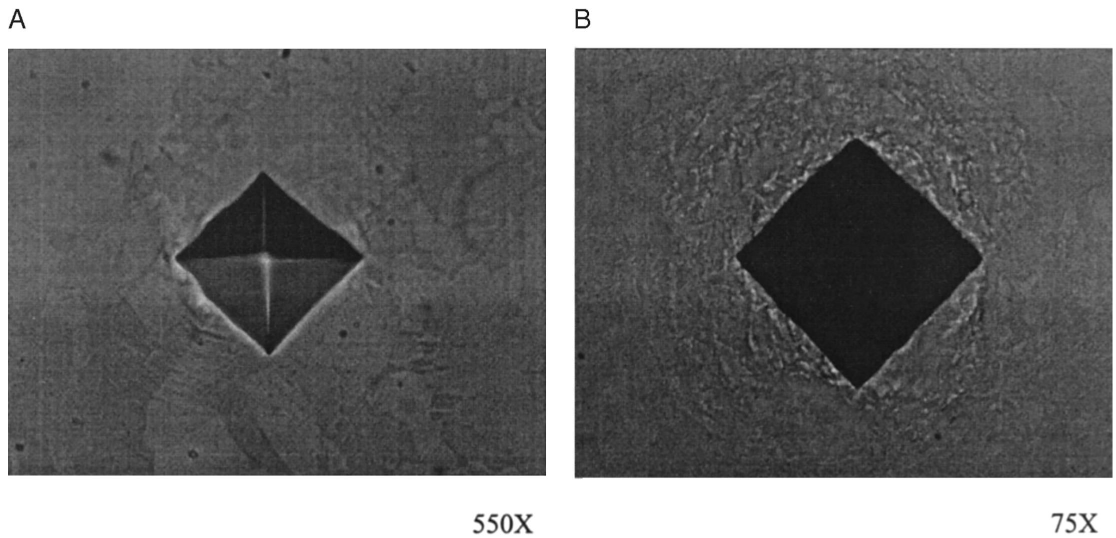

Figure 5. A comparison of the deformation around an indentation as a function of the force applied. For (**A**), a 100-g load was applied, resulting in a 41-μm-diameter indent, while for (**B**), a 10-kg load was applied, resulting in a 410-μm-diameter indent.

limiting the extent of the deformation. For example, Figure 5 displays a brass specimen with a hardness value of ~100 HV where loads of both 100 g and 10 kg have been applied. The 100-g load would be recommended. In the case of more brittle materials, such as ceramics, using too heavy a load can result in cracking of the specimen, evident at the corners of the indents, as well as chipping of the material around the indentation perimeter. Examples of materials, recommended loads, test methods, and typical hardness values are shown in Table 3.

Other concerns relate to the velocity of the indenter as it approaches the specimen, and the dwell time of the applied load. If the indenter impacts the specimen instead of applying the force, the repeatability of the test is compromised. This is also the case if the machine is set for short dwell times, since material creep rate is fastest at the beginning of the cycle. In general, creep is most readily observed during testing of low-melting-point metals at room temperature and in many metals at elevated temperatures. Hardness standards recommend a temperature range and dwell times to provide repeatable results. However, when working with low-melting point alloys and other materials more prone to creep, such as plastics, longer dwell times are suggested. In general, when creep occurs during indentation, the operator should permit the indenter to reach equilibrium before removing the load.

Table 3. Examples of Materials with Recommended Loads, Test Methods, and Typical Hardness Values[a]

	HRC (150 kgt)	HRB (100 kgf)	Brinell (10-mm steel ball)	HV (500 gf)
Nonaustenitic Steel			3000 kgf	500 gf
	60	NA	NA	697
	48	NA	451	484
				300 gf
	25	NA	253	266
	NA	93	200	200
	NA	60	107	107
Nickel and high-nickel alloys				
	36	NA	329	344
	NA	54	100	100
Cartridge brass (70% Cu/30% Zn)			500 kgf	100 gf
	NA	92.5	164	190
	NA	89	150	177
Wrought aluminum				
	NA	89	150	177
	NA	28	70	80

[a]NA, not available.

PROBLEMS

Problems are best detected by routine verification procedures. Calibrated test blocks are available to determine if the tester is in working condition; these can also serve as a training aid for new operators. The acceptable error observed from machine to machine using a known standard is dictated by the test standards. Some of the common problems observed are outlined in the following sections.

Instrument Errors

Concerns with the instrument are as follows: indenter-shape deviations, test-force deviations, velocity of force application, vibrations, angle of indentation, and indentation time. If the tester has passed calibration, the indenter shape, test force, and force velocity should be known. Vibrations arise from a combination of the work environment and robustness of the tester; often a vibration table will eliminate this concern. The indenter should be perpendicular to the specimen at the point of contact. The angle of indentation is determined by a combination of the machine and how well the specimen is secured and prepared. For some testers, this will be evident by an asymmetric indentation. Time should be held constant from test to test, but in most cases is a variable controlled by the operator.

Measurement Errors

The most common error is simply operator bias. It is common for each individual to measure an indent slightly undersized or oversized in comparison to another operator. Operators who do this work routinely, however, are self-consistent. Other measurement errors tend to be due to limitations of the equipment. In order to accurately measure the diameter or depth, the measuring device should be calibrated. For the visual measurement of small indentations, additional concerns are the resolving power of the objective (Buckle, 1954 and Buckle, 1959) or camera, and adequate lighting or image quality.

Material Errors

The quality of polish, poor surface finish, and low reflectivity can limit the feasibility of conducting a test, particularly if the indent diameter needs to be measured. Hardness values of highly porous specimens are referred to as apparent hardness values, since the measurement includes the compression of the pores along with the materials. When thickness is a concern, one should examine the backside of the test piece after conducting the test. If there is any sign of the indent's position, such as a bulge, the test piece was too thin. In some cases, after the removal of the indenter, elastic recovery can change the size and shape of the indentation. Changes tend to be more substantial in hard materials than in soft ones, as far as elastic recovery is concerned (O'Niell, 1967). However, distortion of the indent can also occur in the form of ridging or sinking around the indentation, making accurate visual measurements more difficult (Brown et al., 1951).

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Boyer, 1987. See above.

A practical overview of hardness methods and applications is contained in this book as well as an appendix of equipment and manufacturers.

Vander Voort, 1984. See above.

A historical overview of the development of hardness methods as well as application notes.

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APPENDIX: CALCULATIONS OF THE HARDNESS VALUES

This appendix provides the equations with which the measured dimension, depth or diameter, is used to calculate the hardness value for each test.

Brinell

$$\text{HBS or HBW} = 0.102 \times \frac{2F}{\pi D(D - \sqrt{D^2 - d^2})} \tag{1}$$

where D = diameter of the ball in mm, F = test force in N, and d = mean diameter of the indentation in mm. The Brinell hardness is denoted by the following symbols: HBS in cases where a steel ball is used or HBW in cases where a tungsten carbide ball is used.

Rockwell

Rockwell tests scales, A to Z, correlate with the choice of indenter and test force applied. The equations however are based on three cases as shown below.

1. Rockwell Test with Brale Indenter

$$\text{hardness} = 100 - e \tag{2}$$

where e = permanent increase in depth of penetration under preliminary test force after removal of the additional force, the increase being expressed in units of 0.002 mm.

2. Rockwell Test with Ball Indenter

$$\text{hardness} = 130 - e \tag{3}$$

where e = permanent increase in depth of penetration under preliminary test force after removal of the additional force, the increase being expressed in units of 0.002 mm.

3. Superficial Rockwell Test

$$\text{hardness} = 100 - e \tag{4}$$

where e = permanent increase in depth of penetration under preliminary test force after removal of the additional force, the increase being expressed in units of 0.001 mm.

Vickers, Knoop, and Berkovitch

The same tester can be used for all three tests below. The equation is determined specifically by the indenter employed.

Vickers

$$\text{HV} = \frac{1854.4P}{d^2} \tag{5}$$

where P = test force in gf, d = mean diagonal of the indentation in μm, and a square-based, pyramidal indenter with a 136° angle is used.

Knoop

$$\text{HV} = \frac{14{,}229.4P}{d^2} \tag{6}$$

where P = test force in gf, d = long diagonal of the indentation in μm, and a rhombic-based, pyramidal indenter with included longitudinal edge angles of 172°, 30 min, and 130°, 0 min, is used.

Berkovich

$$\text{HV} = \frac{1569.7P}{d^2} \tag{7}$$

where P = test force in gf, d = diagonal of indentation in μm, and a triangular pyramid indenter with an angle of 115° is used.