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Introduction to Hardness Testing

Hardness has a variety of meanings. To the metals industry, it may be thought of as resistance to permanent deformation. To the metallurgist, it means resistance to penetration. To the lubrication engineer, it means resistance to wear. To the design engineer, it is a measure of flow stress. To the mineralogist, it means resistance to scratching, and to the machinist, it means resistance to machining. Hardness may also be referred to as mean contact pressure. All of these characteristics are related to the plastic flow stress of materials.

Measuring Hardness

Hardness is indicated in a variety of ways, as indicated by the names of the tests that follow:

- *Static indentation tests:* A ball, cone, or pyramid is forced into the surface of the metal being tested. The relationship of load to the area or depth of indentation is the measure of hardness, such as in Brinell, Knoop, Rockwell, and Vickers hardness tests.
- *Rebound tests:* An object of standard mass and dimensions is bounced from the surface of the workpiece being tested, and the height of rebound is the measure of hardness. The Scleroscope and Leeb tests are examples.
- *Scratch file tests:* The idea is that one material is capable of scratching another. The Mohs and file hardness tests are examples of this type.
- *Plowing tests:* A blunt element (usually diamond) is moved across the surface of the workpiece being tested under controlled conditions of load

and shape. The width of the groove is the measure of hardness. The Bierbaum test is an example.
- *Damping tests:* Hardness is determined by the change in amplitude of a pendulum having a hard pivot, which rests on the surface of the workpiece being tested. The Herbert Pendulum test is an example.
- *Cutting tests:* A sharp tool of given shape is caused to remove a chip of standard dimensions from the surface of the workpiece being tested.
- *Abrasion tests:* A workpiece is loaded against a rotating disk, and the rate of wear is the measure of hardness.
- *Erosion tests:* Sand or other granular abrasive is impinged on the surface of the workpiece being tested under standard conditions, and loss of material in a given time is the measure of hardness. Hardness of grinding wheels is measured by this testing method.
- *Electromagnetic testing:* Hardness is measured as a variable against standards of known flux density.
- *Ultrasonic testing:* A type of indentation test

In the following chapters, most of these methods are covered. However, the focus is on static indentation tests, because they are the most widely used. Rebound testing is also used extensively, particularly for hardness measurements on large workpieces or for applications in which visible or sharp impressions in the test surface cannot be tolerated.

Common Concepts of Hardness

The hardness test is, by far, the most valuable and most widely used mechanical test for evaluating the properties of metals as well as certain other materials. The hardness of a material usually is considered resistance to permanent indentation. In general, an indenter is pressed into the surface of the metal to be tested under a specific load for a definite time interval, and a measurement is made of the size or depth of the indentation.

The principal purpose of the hardness test is to determine the suitability of a material for a given application, or the particular treatment to which the material has been subjected. The ease with which the hardness test can be made has made it the most common method of inspection for metals and alloys.

Why so valuable? Principally, the importance of hardness testing has to do with the relationship between hardness and other properties of material. For example, both the hardness test and the tensile test measure the resistance of a metal to plastic flow, and results of these tests may closely parallel each other. The hardness test is preferred because it is simple, easy, and relatively nondestructive.

Hardness is not a fundamental property of a material. Hardness values are arbitrary, and there are no absolute standards of hardness. Hardness has no quantitative value, except in terms of a given load applied in a specified manner for a specified duration and a specified penetrator shape.

Current practice in the United States divides hardness testing into two categories: macrohardness and microhardness. Macrohardness refers to testing with applied loads on the indenter of more than 1 kg and covers, for example, the testing of tools, dies, and sheet material in the heavier gages. In microhardness testing, applied loads are 1 kg and below, and material being tested is very thin (down to 0.0125 mm, or 0.0005 in.). Applications include extremely small parts, thin superficially hardened parts, plated surfaces, and individual constituents of materials.

Hardness Testing Theory

Early methods generally consisted of scratching. Scratch hardness testing consists of penetration of the material surface by a testing point and bears a close resemblance to the indentation hardness test. One of the earliest forms of 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. In 1822, the Mohs scale of hardness was introduced for minerals and measures the relative hardness of ten minerals. For more information, see Chapter 6.

Other scratch-hardness tests have been used in the metalworking industry, primarily on a laboratory basis. One of the better known is the Spencer Bierbaum instrument. The principle involved consists of mechanically drawing the specimen under the diamond, which is lubricated by a fine watch oil during the scratching operation. After the scratch is made, the sample is cleaned of oil. The width of the scratch is read in microns by means of a filar micrometer eyepiece. The scale is derived by using the reciprocal of the cut width in microns squared, multiplied by 10,000:

$$K = 10{,}000/W^2$$

where K is the microcharacter scale, and W is the width of cut in microns.

In the late 19th century, more attention was paid to hardness and its measurement. Johann A. Brinell, a Swedish engineer, presented a paper to the Swedish Society of Technologists describing his "ball" test. This rapidly became known as the Brinell test and became universally used in the metalworking industry. Currently, many machines have been devised for making these tests more rapidly and accurately, but the principle has remained essentially unchanged.

Because of the limitations imposed by the Brinell method and increased engineering requirements, several investigators intensified their efforts toward devising other indenters—principally those made from diamond—to accommodate the testing of fully hardened steels. In 1919, the Rockwell test was introduced. It has become, by far, the most popular hardness test in use today, mainly because it overcomes the limitations of the Brinell test. The inventor, Stanley P. Rockwell, a Hartford, Connecticut, heat treater, used the test for process control in heat treating.

Hardness values in Rockwell type tests may be expressed as $C \times Y$, where C is the constraint factor for the test, and Y is the uniaxial flow stress of the material being tested. The value of the constraint factor depends mainly on the shape of the indenter used. Many of the common indenters (Brinell, Vickers, and Knoop) are relatively blunt. Their constraint factor is approximately 3.

Prandtl first explained the origin of the constraint factor, C. He likened the blunt hardness indenters used in engineering to a flat-ended punch and proceeded to calculate the mean stress on a two-dimensional punch—that is, one having height and width but no appreciable thickness—for the onset of plastic flow beneath the punch. He assumed a flow pattern beneath the punch that satisfied kinematics. The material within the pattern was assumed to flow plastically in plane strain, and the material surrounding the flow pattern was considered to be rigid. The flow pattern determined by Prandtl, which is shown in Fig. 1(a), predicts a constraint factor C of $1 - (\pi/2)$.

Hill generalized Prandtl's approach into what is now known as the slip-line-field theory. Conditions of equilibrium need not be satisfied in the slip-line-field approach, and hence, a unique solution is not obtained. For each kinematically admissible flow pattern, an upper-bound solution is obtained. Hill proposed the slip-line-field solution shown in Fig. 1(b), which leads to the same value of C as the pattern determined by Prandtl ($C = 2.57$). According to these theories, the material displaced by the punch is accounted for by upward flow. Constraint factor C may be termed a "flow constraint" from the slip-line-field point of view.

The calculated value of 2.57 is reasonably close to the observed value of 3, particularly considering that the calculation is for a two-dimensional punch, whereas the actual indenter is three-dimensional. Shield extended the plane-strain slip-line-field solution of Hill to a flat-ended circular punch (Fig. 2). In this instance, the pressure on the punch, and on the material beneath the punch, is not uniform but decreases near the outer surface of the punch where constraint is less. The value of *C* in this instance was calculated to be 2.82—even closer to 3 than for the two-dimensional punches.

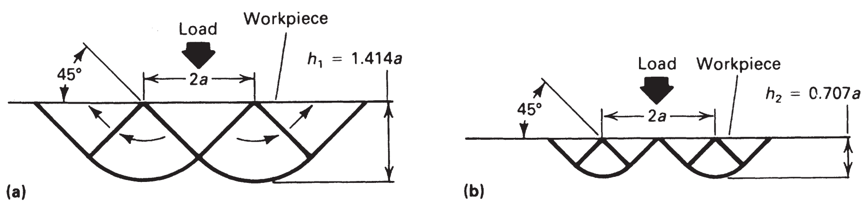

Fig. 1 Slip-line-field solutions for a flat-ended two-dimensional punch having a width of $2a$. (a) Prandtl's flow pattern. Flow in unshaded area is downward and to left and right, as indicated by arrows in shaded areas. (b) Hill's flow pattern. Flow is to left and right in directions indicated by arrows in (a), but is separated. Source: A.R. Fee, R. Segabache, and E.L. Tobolski, Introduction, *Mechanical Testing,* Vol 8, *ASM Handbook,* ASM International, 1985, p 72

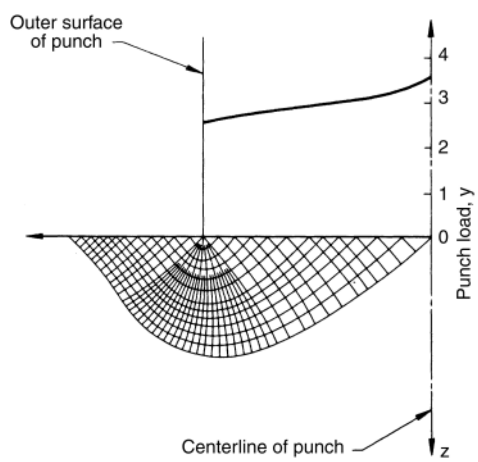

Fig. 2 Slip-line-field solution for a flat-ended circular punch. Source: R.T. Shield, On the Plastic Flow of Metals Under Conditions of Axial Symmetry, *Proc. Roy. Soc.,* Vol A233, 1955, p 267

Because of the reasonably close agreement between the observed and calculated integrated force on a hardness indenter, the slip-line-field explanation for *C* has been widely accepted. However, when a large block of material is loaded by a spherical indenter, flow patterns such as those shown in Fig. 3(a) and (b) are obtained. These flow patterns bear little resemblance to those determined by Hill and Shield. The extent of the region of fully developed plastic flow may be determined precisely by sighting along the deformed grid lines and observing the area as outlined by the circular line in Fig. 3(b). This line separates the elastic region (outside the line) from the fully plastic region (inside the line).

The circular line in Fig. 3(b) resembles one of the lines of constant maximum shear stress for the elastic solution determined by Hertz for a rigid spherical indenter of very large radius that is pressed against an elastic, semi-infinite body. Figure 4 shows the spherical interface between the indenter and the body as a flat surface, and the values of M' on the lines of constant maximum shear stress are equal to the ratio of the maximum shear stress in the body to the mean stress (unit load) on the indenter.

The elastic-plastic boundary in Fig. 3(b) is found to correspond closely to the dashed line of Fig. 4, for which $M' = 0.18$. If the maximum shear stress on this line is assumed to equal $(Y/2)$ by the maximum-shear theory, then the mean stress on the indenter will be $(Y/2)$ $(M') = 2.8$. This corresponds to a constraint factor *C* of 2.8, which agrees with the results of Shield.

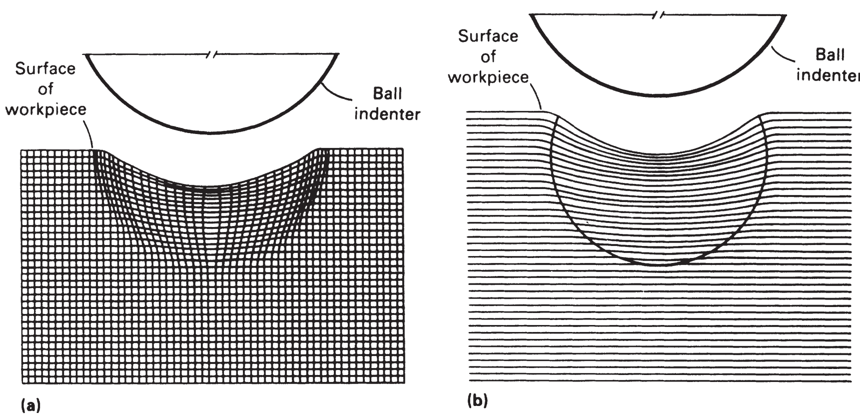

Fig. 3 Deformed grid pattern on a meridianal plane in a Brinell hardness test. (a) Modeling clay. (b) Low-carbon steel. Source: A.R. Fee, R. Segabache, and E.L. Tobolski, Introduction, *Mechanical Testing,* Vol 8, *ASM Handbook,* ASM International, 1985, p 72

Shaw and DeSalvo (Ref 1) have shown that if the test piece (workpiece) extends at least 10*d* (where *d* is the diameter of the indentation) in all directions from the indenter, the displaced volume may be accounted for by the elastic decrease in volume. Therefore, there is no need for upward flow, and the elastic theory is in complete agreement with Fig. 3. The constraint factor that arises here is an elastic-constraint factor because the displaced volume is accommodated by an elastic decrease in volume instead of by upward flow, as in the slip-line-field approach.

The basic difference between the slip-line-field and elastic theories of hardness lies in the assumption regarding the behavior of the material that surrounds the plastic zone. The slip-line-field theory assumes this material to be rigid, whereas the elastic theory assumes it to be elastic. As shown in Fig. 3, the flow pattern for a blunt indenter operating on a semi-infinite body does not correspond to that derived using the plastic-rigid theory (Fig. 1). However, experiments with blunt punches may be devised that do produce the flow patterns of Prandtl and Hill shown in Fig. 1(a) and (b). By placing a layer of modeling clay of thickness $h = 1.414a$ (where a is the half-width of the punch) on a steel substrate (Fig. 5a), the plastic-rigid theory is justified (Fig. 1a). As Fig. 5(b) shows, a flow pattern that resembles the Prandtl

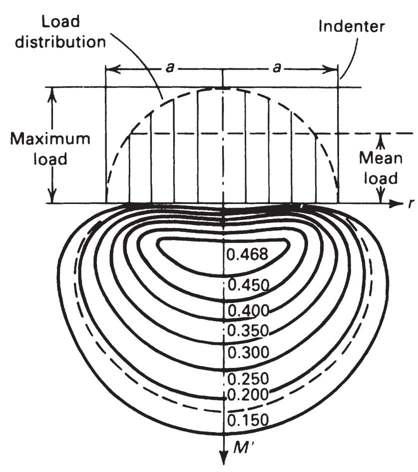

Fig. 4 Hertz lines of constant maximum shear stress on a meridianal plane below the surface of an elastic, semi-infinite body, caused by a frictionless load from a rigid sphere of very large radius. *M′* = maximum shear stress in body divided by mean stress (unit load) on the sphere. Source: A.R. Fee, R. Segabache, and E.L. Tobolski, Introduction, *Mechanical Testing,* Vol 8, *ASM Handbook,* ASM International, 1985, p 72

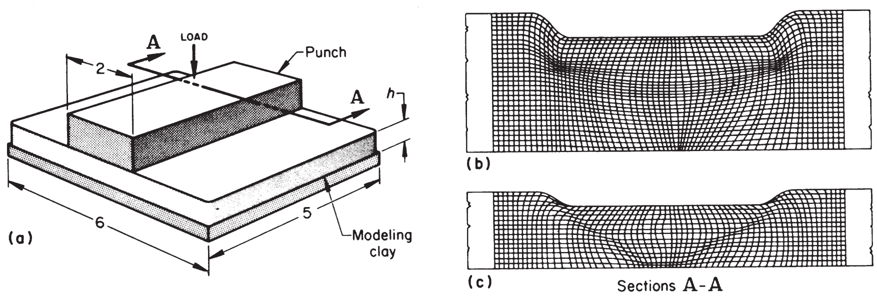

Fig. 5 Grid patterns on transverse planes of modeling-clay specimens in plane strain by a flat punch. (a) Arrangement for the test. (b) Pattern obtained when $h = 1.414a$ as in Fig. 1(a). (c) Pattern obtained when $h = 0.707a$ as in Fig. 1(b). Test specimens of both thicknesses were supported by a rigid steel plate. Source: Hardness Testing, *Nondestructive Inspection and Quality Control,* Vol 11, *Metals Handbook,* 8th ed., American Society for Metals, 1976, p 3

slip-line-field solution is obtained. Similarly, when a thinner layer of modeling clay, $h = 0.707a$ (Fig. 1b), is placed on rigid steel substrate, the flat punch produces a flow pattern (Fig. 5c) that closely resembles that in Fig. 1(b).

Figure 3 directly supports the elastic theory of hardness for a blunt indenter. Further support is the fact that shot peening produces residual compressible stresses that are of importance to fatigue life. Although these compressible stresses are consistent with the elastic theory, they are not included in the slip-line-field theory.

According to the elastic theory, when a blunt indenter is pressed into a plane surface, material beneath the indenter deforms plastically without upward flow, and the elastic stress field is the same as though there were no plastic flow. When the load is removed, there is "plastic recovery"—that is, plastic deformation in a direction opposite to the initial flow but over a smaller volume. Because plastic recovery is not complete, biaxial residual compressible stresses remain in planes parallel to the free surface after the load is removed.

The elastic theory suggests that strain-hardening tendency and friction on the indenter surface should not influence constraint factor C. Alternatively, the slip-line-field theory suggests that increased friction on an indenter will cause an increase in constraint factor C. The solid lines of Fig. 6 correspond to the slip-line-field solution for a Vickers indenter with zero friction, and the dashed lines are for a case with friction. The constraint factor C in both instances will be $1 + \psi$, and C obviously will be greater with friction. A similar shift in the slip-line pattern takes place when the work metal tends to

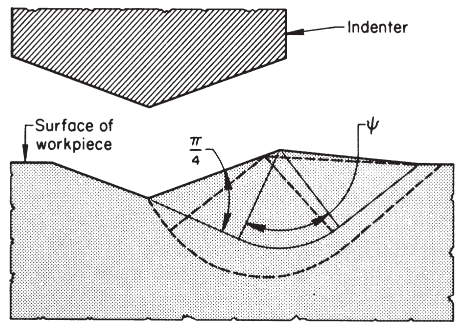

Fig. 6 Slip-line-field solution for two-dimensional indentation. Solid lines correspond to the frictionless case, where ψ = 70; dashed lines correspond to the case with friction. The pattern for a frictionless indenter acting on annealed material will also resemble the dashed line pattern. Source: Hardness Testing, *Nondestructive Inspection and Quality Control,* Vol 11, *Metals Handbook,* 8th ed., American Society for Metals, 1976, p 3

work harden. Therefore, the slip-line-field theory suggests that an increase in the constraint factor C occurs with a tendency toward work hardening and with increased friction.

Types of Hardness Tests

Indentation Tests. In this instance, the hardness is evaluated by the amount of permanent deformation, or plastic flow of the material. The amount of flow may be determined by measuring the depth of the indentation or by measuring the area. As the test material becomes softer, the depth of penetration becomes greater. Likewise, the projected area increases as the test material becomes softer.

By one of the most common methods of hardness testing (Rockwell), hardness is determined by the depth of the indentation in the test material resulting from application of a given force on a specific indenter. In the Brinell test, by comparison, hardness is determined by the impression created by forcing a specific indenter into the test material under a specific force for a given length of time. However, in higher automated Brinell testing systems, hardness is evaluated by depth of the impression, which makes it similar to the Rockwell test in basic principle.

Microhardness Testing. As stated earlier, microhardness indicates that the applied load on the indenter is no greater than 1 kg. As a rule, microhardness is evaluated by measuring the area of the indentation rather than the depth. This subject is discussed in Chapter 6.

Special Indentation Tests. Modifications of this type test have been developed, and a few have had some commercial acceptance. Perhaps the best example is the Monotron test. This instrument used a 0.75 mm (0.03 in.) hemispherical diamond indenter. The Monotron principle was the reverse of the more conventional indentation testers such as the Brinell and Rockwell. Instead of using a prescribed force and measuring the depth or area, the Monotron indenter was forced into the material being tested to a given depth, and the hardness was determined by the force required to achieve this depth of penetration. This instrument was developed primarily for evaluating the true hardness of nitrided cases, which were, at one time, difficult to evaluate accurately. The Monotron has not been manufactured for many years, and it is doubtful whether any are still in use.

Rebound Principle. The Scleroscope (Shore Instruments, Division of Instron Corp., Canton, Massachusetts) and the Leeb are the only two testers based on this concept. The test relates more closely to the elastic limit of the material than to the work-hardening and tensile strength characteristics of indentation tests. It is essentially a dynamic indentation test, in which a diamond-tipped hammer (referred to as a "tup") is dropped from a fixed height onto the surface of the work material. The height of the hammer rebound is a measure of the material hardness.

Scratch Hardness Test. At least two instruments have been designed in the United States for quantitatively measuring hardness by the scratch method. The earlier and less familiar one was designed by Professor Graton of Harvard. One instrument, built at the Geophysical Laboratory, was intended to overcome the disadvantages of the Mohs scale by eliminating the personal judgment factor and by reducing the overlap of hardness ranges of various minerals. The instrument consisted primarily of a microscope, stage, sliding weight to apply loads to 3 g, and a diamond point. The diamond was ground to a semicircle, bladelike edge with a 45° included angle. In operation, the mineral being tested is scratched by the diamond, and the scratch is compared with standard limit scratches in the microscope eyepiece. Another form of scratch-hardness testing uses a file. Both of the above methods are covered in Chapter 6.

Abrasion and Erosion Testing. Because hardness is commonly associated with wear or resistance to wear, one is often used to evaluate the other. However, these tests are slower than indentation hardness tests. Selection of materials for specific applications is often done on the basis of wear resistance, which is directly related to hardness. So abrasion testing of some type is often used.

Wear rates are critical to improving the service life of parts that ordinarily fail by wear. Wear testing may be required to evaluate whether the observed wear rate is normal for the application.

Wear tests generally are less accurate and less reliable than tests of other engineering properties of materials or components. Because there is no universal wear test, wear rates are evaluated by many different procedures. Each is designed to evaluate a specific type or mechanism of wear. A wear test is not a viable engineering evaluation unless it is:

- *Reliable*: Capable of producing wear of a certain material in a predictable and statistically significant manner
- *Able to rank materials:* To provide statistically significant differences in wear rates among different types of materials
- *Valid:* Capable of accurately predicting the service performance of a given material

Wear rates can be assessed by either service testing or laboratory testing in a controlled or artificial environment. Few service tests can meet the necessary criteria of reliability and ranking ability. Field tests seldom justify confidence, and laboratory tests usually are conducted under artificial conditions that differ significantly from actual service conditions and thus may be of questionable validity.

Laboratory Wear Tests. An abrasive is normally used. These tests cannot be considered more than preliminary screening evaluations; and they can be misleading in material selection unless they accurately simulate:

- Hardness and particle size of the specific abrasive (generally, the hardest substance in an abrasive mixture) in the environment that controls wear in service
- Forces causing contact between the abrasive particles and the wear surface (contact pressure)
- Relative motion (both speed and direction) between the abrasive and the wear surface

Two abrasive-wear tests—one simulating high-stress grinding abrasion (Fig. 7) and the other simulating low-stress scratching abrasion (Fig. 8)—are known to be reliable and are used to rank materials. Because some of the material properties that appear to provide good resistance to abrasive wear also seem to provide good resistance to adhesive wear, abrasive-wear tests may be used to rank materials for adhesive-wear applications. Nevertheless, such tests never truly simulate adhesive or corrosive wear and thus should not be used as the sole criterion for evaluation.

Service Tests. Even in these tests, results should be used with caution. Unfortunately, most service situations are subject to great variability, and it may be impossible to find a single material that is best suited for a given application.

Electromagnetic Testing. There are innumerable cases in the metalworking industry where one property or function is measured in terms of another. Temperature measurement is a notable example. The thermocouple in a heat treating furnace does not offer a direct measurement of temperature; it registers difference in emf, which is converted to temperature. Hardness is sometimes

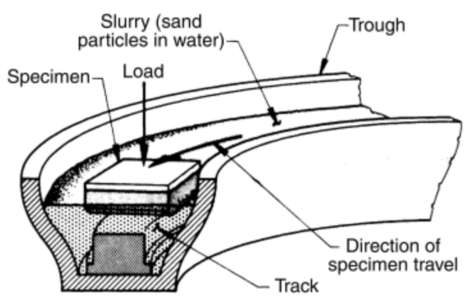

Fig. 7 Schematic illustration of a wet-sand abrasion test. This is a well-validated wear test simulating high-stress grinding abrasion. Source: Wear Failures, *Failure Analysis and Prevention,* Vol 10, *Metals Handbook,* 8th ed., American Society for Metals, 1975, p 153

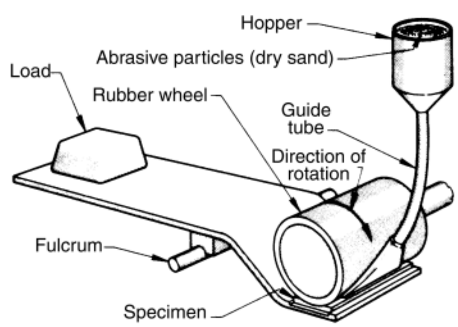

Fig. 8 Schematic illustration of a dry-sand erosion test used for evaluating resistance to low-stress scratching abrasion. Source: Wear Failures, *Failure Analysis and Prevention,* Vol 10, *Metals Handbook,* 8th ed., American Society for Metals, 1975, p 153

evaluated in terms of changes in some other property such as magnetic characteristics.

The electromagnetic test is not a hardness test per se, but can be used for sorting steel parts on the basis of hardness. Low-frequency comparator-bridge-type instruments are most commonly used. Reference coils are initially balanced with sample parts of known hardness. Parts of unknown hardness are then substituted for one of the reference parts. The degree of unbalance that results is then correlated with differences in hardness. Additional information on this method, including the equipment and techniques, is presented in Chapter 6.

Classes of Tests

Tests should be conducted by experienced personnel. There are three classes of tests:

Class 1. Single parts or representative samples from large lots are tested in shops and laboratories. Test equipment must be accurate and versatile.

Class 2. Two subclasses are involved in this instance. In one, speed of testing is essential, as in production line applications where parts are similar in physical size and shape. Commonly used testing equipment is typically modified for the purpose. There is some loss in testing accuracy. In the other subclass, there is less emphasis on speed of testing. Testing machines vary from large, customized, semicontinuous types capable of testing large numbers of similar parts, down to small, portable instruments used to test large castings that are outside the range of conventional equipment.

Class 3. Testing equipment in this instance may be of the same high caliber as that used in Class 1. But there are major differences: Most of this type of testing is on a laboratory basis and mainly in laboratories concerned with process control. Also, several different types of testing machines may be used in thorough testing studies. Microhardness testing is an example.

Primary Hardness Test Machines

Note: Recent events have warranted the need for Primary hardness test machines. A Primary machine is one that calibrates test blocks at the highest level, usually by a government agency. These machines provide Primary standards from which all other machines and test blocks base their hardness readings. In the United States, one such machine exists at the National Institute of Standards and Technology (NIST) in Gaithersburg, Maryland. A Primary hardness test block from NIST would be referred to as a Hardness SRM (for Standard Reference Material). In recent years, other countries have been establishing traceable hardness standards and accreditation procedures. At some time in the future, all measurements in hardness could be coordinated through national agencies and their accredited bodies.

REFERENCE

1. M.C. Shaw and G.J. DeSalvo, On the Plastic Flow Beneath a Blunt Axisymmetric Indenter, *Trans. ASME,* Vol 92, 1970, p 480