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The Evolution of Hardness Testing

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Early hardness test block calibration laboratory's used analog, deadweight Rockwell testers. *Source: Wilson Hardness*

A Production Brinell system can perform fully automated, depth-of-penetration testing for 100% inspection of railroad wheels. *Source: Wilson Hardness*

Hardness testing methods have been in use in various formats for more than two centuries and have provided valuable and pertinent material information throughout this time, from the industrial revolution to world wars to space exploration and, most recently, the electronics and information age. During these years, hardness testing has evolved quite dramatically from simple scratch-testing to motorized testers to today's sophisticated, fully automated, computer-controlled systems.

From its early origins in scratch testing, circa 1722, the development of hardness testing instrumentation has been consistent with evolving technology and, in many ways, the refinements paralleled engineering accomplishments of the relevant era.

Some of the first types of hardness tests originated on bars that varied in hardness from end-to-end. The concentration at which the material being tested could form a scratch on the bar was a determining factor in the specimen's hardness. These early, crude forms gave a relative and often comparative indication of material strength and were adequate for the time. More refined forms of scratch testing were introduced during the 1800s by a German mineralogist named Friedrich Mohs. In what eventually became known as the Mohs hardness test, the user would scratch an unknown sample with a material of known hardness. Later, this test was improved to a more standardized format and involved scratching material surfaces with a diamond and measuring the width of the resultant line. Mohs chose a diamond, of course, based on its property as the hardest known natural substance and the fact that a diamond can produce a scratch on virtually all other substances. This refined test utilizes a scale from 1-10, the higher the value, the harder the material. In some processes the Mohs method is still utilized today. Varying scratch-test forms continued to be introduced over the next 100 years or so, none really gaining a hold in materials testing the way the Mohs test did.

The first transformation to a more systematic testing format came with the introduction of the indentation test. The earliest form was introduced in 1859 and was based on the force required to produce a 3.5 mm indent in the test material. The depth was measured with a vernier scale system and the total weight needed to reach the 3.5 mm was indicated as the hardness. The penetrator consisted of a truncated cone that tapered from 5 mm at the top to 1.25 mm at the point. This method was mostly effective with soft materials.

The first widely accepted and standardized indentation hardness test was proposed by J. A. Brinell in 1900. His goal was to find a consistent and fast means of determining material hardness. The Brinell hardness test, still widely used today, consists of indenting the metal surface with a 1 to 10 mm diameter ball at heavy loads of up to 3,000 kg. The resultant circular impression was, at the time, measured with a low-power manual eye microscope. The diameter of the impression was then mathematically calculated to a hardness value. The Brinell test essentially introduced the production phase of indentation hardness testing and opened the way for additional indentation tests that were more relevant to material types. Today, the Brinell test remains common in testing aluminum and copper alloys (at lower forces) and steels and cast irons at the higher force ranges. The test method is particularly useful in certain material finishes as it is more tolerant of surface conditions due to the indenter size and heavy applied force. Brinell testers are often manufactured to accommodate large parts, such as engine castings and large-diameter piping. Today, in addition to the still widely used manual microscopes, automatic camera systems are capable of rapid and extremely accurate result generation.

While the Brinell test proved to be an effective and productive means of material testing, and surely contributed to ushering in a new standardized era in hardness testing, it did have limitations. For one, the relatively large size of the indenter, along with the high test forces, made it inadequate for small precision-type testing. The nature of the test also requires a second operation to measure the indent. In addition, the heavy force required by the test leaves an obvious and potentially damaging impression, so finished goods testing is not always practical. For these reasons, as well as the increasingly high demand for reliable and productive testing techniques that were the byproduct of the time-notably the industrial age and the record-breaking levels of machinery and component manufacturing in support of both World Wars-the hardness testing element of material analysis remained restless for change. The race was on to develop even more efficient methods.

With that came the first acceptable alternative to the Brinell, the Vickers hardness test, which partially solved the problem by providing a more consistent, lighter load hardness test. Developed in the U.K. in 1924, the test used the same principle as the Brinell, that of a regulated impression, but utilized a pyramid-shaped diamond rather than the Brinell ball indenter. The resultant impression or un-recovered area is measured using a high powered microscope in combination with filar measuring eyepieces. Later, in 1939, an alternative to the Vickers test-called the Knoop test-was introduced by the U.S. National Bureau of Standards. The Knoop test utilized a shallower, elongated format of the diamond pyramid and was designed for use under lower test forces than the Vickers hardness test, allowing for more accurate testing of brittle or thin materials. These test methods are widely used today in the analysis of small test areas, brittle materials, case hardened and steel components, coatings, wire and other precision parts but now often utilize much more advanced indentation and measuring techniques.

Still, a desire and a drive towards even more efficient test methods remained and the answer became the Rockwell indentation test. The Rockwell method, originally introduced in a basic form in 1914, essentially revolutionized hardness testing, using displacement measurement and thereby producing a direct-reading result, eliminating the need for time-consuming secondary measuring operation. With full cycle-test-time requiring about 12 seconds, and in some cases as little as 3 seconds, the desired productivity and efficiency, along with accuracy, was finally realized. The methods patent application was approved in 1919 and, in 1924, an improved design patent was granted. Simultaneously, commercial production of Rockwell testers was underway and it became the primary, preferred method for testing, enduring in that significance today.

With the primary test methods, Brinell, Knoop, Vickers and Rockwell now defined and firmly established as useful and reliable material test techniques, it was left to technology to methodically and more dramatically improve on the instruments that performed the tests, as well as the processes to make these tests as efficient and accurate as possible. Notable in late the 20th century was the introduction of load cell force regulation in response to the need for improvements to the highly mechanical, traditional deadweight systems, which were very labor intensive to manufacture and required considerable maintenance to sustain accuracy and standards compliance. Closed-loop design is based on transducer technology electronically measuring the force being applied during actuation of the indenter, usually by a servo motor, during every test and processing the information back to the control system. The control system is designed to use the feedback to adjust the force application mechanism to apply, at an extremely accurate rate, the desired force. During the early 1990s, this technology was introduced first to Rockwell testers and later to Knoop, Vickers and Brinell systems. Closed-loop quickly gained momentum as a means to achieve extremely accurate and repeatable hardness test results. Today, the technology is a popular and widely used format.

In recent years, significant improvements in hardness testing instrumentation, as well as computer hardware, electronics, imaging algorithms and software capabilities, have opened the door to newer, extremely precise and reliable testing processes that provide results more quickly than ever before. These components and techniques have proven to be beneficial in raising efficiency, speed and accuracy to levels previously not possible, minimizing or eliminating many of the manual techniques used from the onset of the standardized testing period. One means of improving productivity while providing consistency to the process is through automatic indentation and impression reading utilizing image analysis. Over the past several years, and no doubt increasingly in the future, manual processes have and will continue to rapidly give way to automation in every aspect of the testing process. New, extremely efficient techniques in material preparation and handling, mount fixturing, stage movement, results interpretation, analysis and even reporting have been introduced. An important and productive technology being integrated into many hardness systems around the world is automatic stage traversing and image analysis of hardness impressions.

Two of the more common hardness tests mentioned, Knoop and Vickers, have benefited greatly from these advancements. The nature of these test types typically dictates a lower force consistent with the material being tested, usually resulting in extremely small impressions that must be measured at the micron level. Traditional techniques, still practiced today, involve microscopes with objectives of varying resolution integral to the hardness tester, which are used to manually measure the impression through an eyepiece and are based on human interpretation. Predictably, this is time-consuming, inefficient and-in today's fast paced, extreme environment-increasingly unacceptable.

An automatic hardness system typically consists of a fully controllable tester, including an auto-rotating or revolving turret, as well as actuation in the Z-axis, either from the head/indenter housing or from a spindle driven system used for both applying the indent at a predetermined force, as well as for automatically focusing the specimen. Add to this a standard computer with dedicated hardness software, an automatic XY traversing motorized stage and a USB video camera and the result is a powerful, fully automatic hardness testing system. After initial setup with samples and an applicable traverse and parameter program, the system can be left alone to automatically create, measure and report on an almost unlimited number of indentation traverses.

The technology driving image analysis continues to advance, considerably improving the indent measurement process from the earlier, more limited form that had inadequacies in measuring smaller indents and samples with lesser surface finishes. These high requirements in regards to surface preparation, along with process restrictions, meant previous systems were lacking in effectiveness as a complete solution. The capabilities of current and developing cameras, coupled with the processing capacity of today's PCs and continually improving software packages, have significantly improved the accuracy, repeatability and dependability of automatic indentation reading. It is now possible to accurately and repeatedly read smaller-than-ever indents and locate and analyze indents on surfaces and material previously not possible, such as glass. In addition, new developments in microscope objectives and digital-zooming technology are allowing for wider magnification ranges than ever before.

With a push to expand productivity even further, manufactures next introduced the ability to utilize larger-size, automatic traversing XY stages capable of holding two, four or even six samples at a time in an array of fixturing types. Pre-programmed and saved traverses are opened, samples are aligned in holders and with a single click the indentation, reading and reporting of a multitude of traverses on each sample is initiated. Autofocus mitigates any compromise of indent clarity due to small parallelism position variation. Newer software even allows different scales, forces and microscope objectives within and between traverses, creating new possibilities and combinations in multi-sample and case-depth analysis. This fully frees the operator from manually moving the sample from test to test for both the indentation and the measurement process and quickly provides an ROI and benefit that is readily evident and clearly increases the ability to evaluate a variety of materials.

Automated testing also is increasingly beneficial for Rockwell hardness testing, particularly in repetitive pattern requirements such as Jominy testing, where a number of bars can be fully tested and reported, unmanned after one click of the mouse. The use of an automated stage and software integrated with a Rockwell tester capable of automatic actuation allows for multiple sample testing; in some cases, manufactures are automatically testing more than 15 parts on a stage with multiple indents on each part.

As in Knoop and Vickers testing, Brinell testing, a labor intensive and manual process that requires constant human intervention, became a target for improvement and efficiency gains. With many processes requiring 100% inspection and productivity dependent on quick results, it is no surprise that a means to both accelerate the process and mitigate possible manually induced errors became a priority for the method. In reaction, the Production Brinell test was introduced, also in the late 20th century, as a unique method of automatically and accurately determining Brinell hardness in a production environment. Through the use of the Rockwell test principle of measuring depth of penetration to determine hardness, the Production Brinell test eliminates the costly and time-consuming procedures associated with conventional Brinell testing. In the process, the part is pre-clamped with sufficient pressure to prevent it from moving during the test process. Next, the test is performed applying a pre and full test force for a specified dwell time. Upon dwell completion, the part is unclamped. The test result is obtained by measuring the difference between the reference depth and the final depth after recovery has taken place. Production Brinell systems were soon integrated to production automation lines to perform quick and consistent production type Brinell testing. To meet the needs of testing that was required to adhere to the more common, optical Brinell standard, other means of productively performing optical Brinell measurements became available. As an alternative to the hand-held manual optical measuring process, a hand-held digital camera that can accurately and efficiently measure the diameter of the impression automatically using image analysis techniques, was introduced at about the same time. As a result, it became relatively easy to measure Brinell indents through a camera. As the hand-held imaging system, which still required some manual intervention, was lacking in the often-desired production level, the process gave way to development of fully automatic, optical Brinell systems, introduced during the 1990s, which could provide adherence to ASTM E-10 while allowing for fully automated optical testing. The fully integrated automatic optical Brinell testing system can quickly and accurately perform the entire Brinell test process, including accurate indentation application and indent measurement through an image analysis system to autofocus on, identify and record indent size and hardness measurement.

Consistent with recent amazingly and exponentially evolving technology, hardness testing has rapidly evolved in technique, more so in the past 20 years than the previous 100. Limitations in regards to material geometry, surface finish, productivity, efficiency, data manipulation and reporting have been mitigated and are continually undergoing improvement. The result is increased ability and dependence on “letting the instrument do the work,” contributing to substantial increases in throughput and consistency, while freeing up the operator for other responsibilities. With a fully integrated system now available, the labor intensive, subjective and error-prone processes of the past are virtually eliminated and replaced with a significantly more accurate and productive process. **NDT**

A closed-loop, control-design Rockwell tester. *Source: Wilson Hardness*

Tech Tips

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