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Mechanical Testing in Failure Analysis

James F. Lane, Rimkus Consulting Group, Inc.
Daniel P. Dennies, DMS, Inc.

Mechanical Testing Definitions and Basics

The mechanical behavior of materials is described by their deformation and fracture characteristics under applied tensile, compressive, or multiaxial stresses. Determination of this mechanical behavior is influenced by several factors that include metallurgical/material variables, test methods, temperature, and the nature of the applied stresses. In contrast, physical properties are those typically measured by methods not requiring the application of an external mechanical force (or load). Typical examples of physical properties are density, magnetic properties (e.g., permeability), thermal conductivity and thermal diffusivity, electrical properties (e.g., resistivity), specific heat, and coefficient of thermal expansion.

Mechanical testing is an evaluative tool used by the failure analyst to collect data regarding the macro- and micromechanical properties of the materials being examined. The information obtained helps the failure analyst gain an understanding of how the component or system responded to the applied forces. Also, because some mechanical properties can be correlated, tests such as hardness and microhardness of steels can be used to gain an understanding of tensile strength, especially when there is insufficient material to perform tensile testing.

This article introduces the concepts of various mechanical testing techniques and discusses the advantages and limitations of each when used in failure analysis. A more in-depth review of mechanical testing can be found in *Mechanical Testing and Evaluation*, Volume 8 of the *ASM Handbook*, 2000. Table 1 presents the most commonly used tests, the property or properties each provides, and the limitations. The list of techniques discussed herein is the most commonly used by failure analysts but is by no means exhaustive. The focus of this article is on the various types of static load testing, hardness testing, and impact testing. Other specialized testing, such as wear testing, dynamic (high-strain-rate) testing, elevated-temperature creep/stress rupture, residual stress, fracture mechanics, and fatigue testing, are potentially useful to a failure analyst but are used less often and generally provide specific design-related information or confirmation of the failure mechanism.

Mechanical testing is usually used to verify that the material meets the design requirements and specifications, to confirm the typical mechanical properties, or to assess how the material has been altered by the environment and/or temperature of the service conditions. The systems, methodologies, equipment, environment, and human factors that can affect variability in mechanical testing can be illustrated in a fish-bone diagram (Fig. 1).

There are a few important considerations regarding mechanical testing that the failure analyst must keep in mind. These considerations include the test location and orientation, the use of raw material certifications, the certifications potentially not representing the hardware, and the determination of valid test results.

Test Location and Orientation

The location and orientation of test samples for mechanical testing are important to the failure analyst in order to determine the mechanical properties of the material specific to the failure location and load direction. Almost all materials, save perhaps parts made by powder metallurgy processes, demonstrate anisotropic behavior. Anisotropic behavior means that the mechanical properties are different in different directions. For the common wrought products such as bar, extrusion, plate, sheet, and so on, these three orientations are longitudinal, long transverse, and short transverse. For other manufacturing operations such as die forgings, castings, and additive manufacturing, the mechanical property dependency on location and orientation can be even more complex. Therefore, it is important that any mechanical testing be performed in the appropriate location and direction.

Use of Raw Material Certifications

In many failure analyses, the raw material certificate or material test report (MTR) for the raw material used to fabricate the component is available. However, using the mechanical properties from these raw material certificates or MTRs can be problematic.

First, the location and orientation of test samples in most raw material specifications of common wrought products is along the centerline in the longitudinal direction. As the size of the raw material increases, the location may change. In bar stock, the location will shift to the midradius position. The failure analyst must consider if these data represent the location of the failure.

Second, raw material specifications may represent a large amount of material. In carbon streels, low-alloy steels, and aluminum- and copper-base alloys, the raw material certification may represent hundreds of tons of raw material, because the mechanical testing is done on a sampling basis. The superalloy- and titanium-alloy-base raw materials are better because their production is limited to smaller heats but may still represent approximately 5 to 10 tons of raw material. More specific shapes, such as castings and forgings, may be more representative of the actual failed hardware, but that would be dependent on the testing requirements in the specification.

Lastly, the failure analyst must recognize that the testing for raw material certificates is performed as rapidly as possible for the sake of economics, and the one and only goal is to demonstrate that the raw material satisfies the raw material specification. The actual numbers obtained may not be representative of the failed hardware.

Raw Material Certifications Potentially Not Representing Hardware

Another consideration for the failure analyst is that the mechanical testing performed for certain fabricated shapes may not be an exact representation of the actual hardware. Fabrication products such as castings, forgings, and additive manufacturing may use exemplar test bars fabricated at the same time. Raw materials specification for castings may require separately cast bars, "hang-on" bars, or bars cut from a section of the casting. Each test bar will produce mechanical properties that can be correlated to the actual casting based on comparison

Table 1 Commonly used tests for mechanical testing

Test	Property measured	Limitations
Strength/ductility testing		
Unidirectional tension	Ultimate tensile strength Yield strength Proportional limit (curve) Ductility: percent reduction in area and percent elongation	May be insufficient material for standard test specimen Anisotropic materials require multiple samples Properties can be specimen-size dependent
Unidirectional compression	Yield strength Tensile strength Ductility	Components may not be conducive to a test specimen Anisotropic materials require multiple samples
Bend	Ductility	Bending is not a mechanical property but is generally used as a pass/fail evaluation
Hardness testing		
Macroindentation hardness testing		
Rockwell hardness	Hardness	Need smooth surface finish, flat surface, and parallel sides Sample must fit within the machine and be balanced on the pedestal
Brinell hardness	Hardness	Need smooth surface finish, flat surface, and parallel sides Sample must fit within the machine and be balanced on the pedestal
Vickers hardness	Hardness	Test is slow Careful surface preparation of the specimen is necessary Measurement of indentation is operator dependent and results in variation
Microindentation hardness testing		
Vickers hardness	Hardness	Result does not always correlate to bulk material hardness Values vary with applied loads Requires a polished surface
Knoop hardness	Hardness	Result does not always correlate to bulk material hardness Values vary with applied loads Requires a polished surface
Ultrasonic hardness	Hardness	Result does not always correlate to bulk material hardness Requires a polished surface
Nanoindentation hardness testing		
Nanoindentation hardness	Hardness	Result does not always correlate to bulk material hardness Requires a polished surface Designed for thin films/coatings and microconstituents
Dynamic rebound hardness testing		
Scleroscope hardness	Hardness	Requires a flat surface Component must be of sufficient thickness and mass
Leeb (Equotip) hardness	Hardness	Requires a flat surface Component must be of sufficient thickness and mass
Other hardness testing		
Durometer hardness	Hardness	Requires sufficient thickness of component
Pencil hardness	Hardness	Limited to coatings and surface modifications
Impact toughness testing		
Charpy impact	Toughness	Requires sufficient material for standard sample size
Izod impact	Toughness	Requires sufficient material for standard sample size
Drop weight impact	Toughness	Must fit in the test fixture Requires large surface area
Other mechanical testing		
Component testing	Functionality	Nonstandardized test requires effort to determine test parameters and attach points

to a qualification casting but are not the actual mechanical properties. Mechanical properties for forgings may be determined from a prolongation of each forging or from the prolongation from one sample forging or from a qualification forging. Mechanical properties for additive-manufacturing-processed parts are still a work in progress but, if done, are usually taken from test bars fabricated separately during the build. The question for the failure analyst is whether these mechanical properties actually represent the failed hardware.

Determination of Valid Test Results

The test samples for mechanical properties require a substantial amount of raw material. Many times, it is difficult to impossible to perform a mechanical property test in the proper orientation and location on the failed part due to the size of the failed part. Mechanical property testing specifications, such as tensile testing in accordance with ASTM International E 8 (Ref 1), have a range of sizes for test samples. However, the failure analyst must consider that using the smaller-sized test bars may produce data that are not the same or comparable to the established databases for mechanical properties.

Hardness testing is the most common mechanical test used by a failure analyst, typically because it is versatile, quick, inexpensive, portable, and provides a great deal of insight regarding the strength properties of the material. Hardness is used to evaluate the heat treatment condition, estimate the tensile strength, identify microstructural changes due to work hardening or overheating, detect decarburization or surface contamination, and provide a host of other useful information. Because the damage to the component is generally small, hardness testing often can be considered nondestructive. Portable testers allow the analyst to obtain values in the field on samples that are too large or too integral in a system to bring into the laboratory.

Although the versatility of hardness testing makes it one of the most used tools in the analyst's arsenal, it is often one of the most misused tests performed. Understanding the

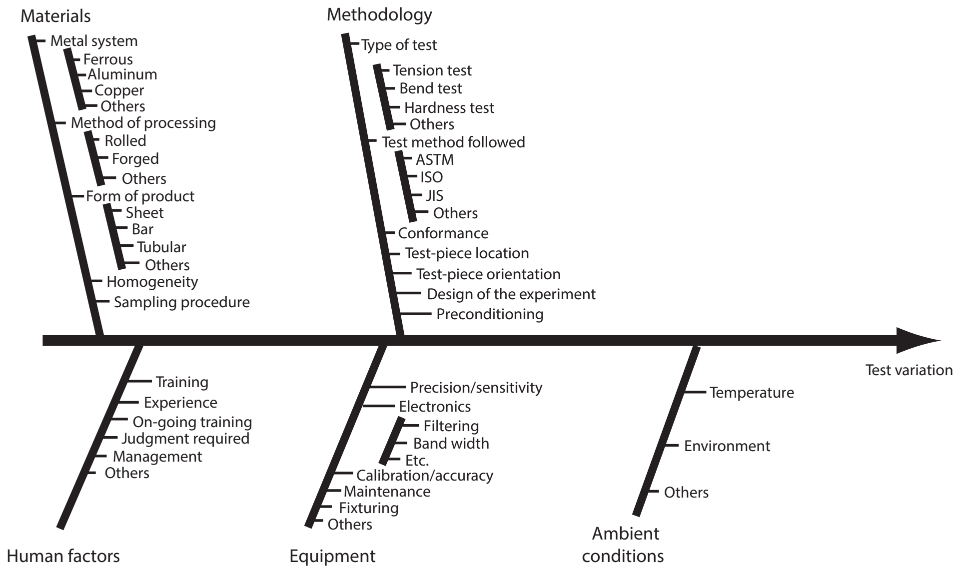

Fig. 1 Fish-bone diagram showing the systems, methodologies, equipment, environment, and human factors that can affect variability in mechanical testing

limitations of the specific testing technique and how to use and properly interpret the data is paramount to understanding how the component(s) are actually responding to the applied loading conditions.

Other mechanical tests are destructive in nature and require the fabrication of a test specimen, so the testing will alter the condition of the sample/component. The analyst must determine not only what mechanical tests will provide the most useful information but also determine the order in which the testing will be performed. Because load testing and impact testing require sectioning, all photography, metrology, fractography, surface analysis, nondestructive testing, and any other examination techniques requiring that the original condition be maintained must be performed prior to destructive testing. This is discussed in more detail in the article "How to Organize and Run a Failure Investigation" in this Volume. In addition, it is always prudent to have a thorough understanding of how the components were affected by the applied loads before any destructive testing is performed.

Exemplar components are components that match the failed component (i.e., the same part number that is hopefully the same production lot and heat treatment batch). The use of exemplars can range from simply being a visual reference in a demonstration to being used for mechanical testing specimens to provide mechanical property data about a particular part or batch of parts. The closer the exemplars are to the failed component (geometrically, fabrication processing history, and chronologically), the more reliable the test data comparison. If a raw material discrepancy is suspected, it may be that other components of the same batch or lot have the same properties. It may also be useful to have exemplars from other production or heat treatment batches for comparison testing.

The failure analyst should exercise care in interpreting mechanical test results, especially when comparing the results to design specifications. Design specifications are usually 8 to 12% lower than the typical/actual mechanical properties for most established materials. A mechanical property above the design specification but below the typical/actual value may indicate a problem with heat treatment and so on. However, even substandard tensile strength does not necessarily indicate the root cause of the component failure. Often, a 5 to 10% reduction in tensile strength below the design requirement is still well within the design safety factors.

Occasionally, the mechanical properties may be acceptable over most of the component but may vary at a bend, heat-affected zone, or other fabrication or assembly variation. Castings can have significant variations in properties from one location to another depending on the solidification practice or thickness of the casting. Thus, the location of the test specimen within the component can also be significant.

Therefore, results from samples from the casting itself may not be directly comparable. Other factors may affect material properties results. Material may have been tested prior to forming or other deformation. Subsequent coatings or surface modifications such as case hardening may have improved or degraded mechanical properties. Variations from one location to another due to local materials processing variations may help explain differences in mechanical properties between the bulk material and the failure origin.

Strength/Ductility Testing

Uniaxial Tension Testing

The tension test is one of the most commonly used tests for evaluating materials. In its simplest form, the tension test is accomplished by gripping opposite ends of a test specimen within the load frame of a test machine. A tensile force is applied by the machine, resulting in the gradual elongation and eventual fracture of the test specimen. During this process, force-extension data, a quantitative measure of how the test item deforms under the applied tensile force, usually are monitored and recorded. When properly conducted, the tension test provides force-extension data that can quantify several important mechanical properties of a material. The mechanical properties that can be determined from tension tests include, but are not limited to:

- Elastic deformation properties, that is, the modulus of elasticity (Young's modulus) and Poisson's ratio (in some instances).
- Proportional limit
- Yield strength and ultimate tensile strength
- Ductility properties, such as elongation and reduction in area
- Strain-hardening characteristics

Uses and Limitations in Failure Analysis

A uniaxial tension test provides a failure analyst the actual, or typical, mechanical properties and an exemplar fracture surface of the material specific to the failure location and load direction. The actual mechanical property and exemplar fracture-surface information of the material is critical in the evaluation of the many aspects of the failure analysis, such as comparison to the design specification, verification of heat treatment condition, comparison to the service loads, determination of failure mechanism, and so on.

Unfortunately, as noted in Table 2, there are limitations to uniaxial tension testing in failure analysis. The first limitation in failure analysis is the physical size of the tensile-test sample. A standard 12.8 mm (0.505 in.) diameter tensile bar is approximately 15 cm (6 in.) in length with 19 mm (3⁄4 in.) diameter threaded ends. Therefore, it may be a challenge for the failure analyst to find enough physical material to produce a tension-test sample or more than one test sample. In most failure investigations, a tensile test away from the fracture is usually possible. However, the issue of physical size is further complicated when the failure analyst attempts to perform a tension test at the specific location and direction/orientation of interest of the failure. In many failure investigations, this is not possible.

There are four smaller tensile bars in tensile-testing specifications that can be used in failure analysis. However, the failure analyst much consider that as the test sample becomes smaller, the mechanical property data produced

Table 2 Advantages and disadvantages of strength/ductility tests

Test	Advantages	Disadvantages
Unidirectional tension	Provides actual mechanical properties of the failed component Provides exemplar fracture surface	Requires sufficient material to produce a standard specimen May not be able to obtain desiredorientation
Unidirectional compression	Provides actual mechanical properties of the failed component vs. material test reports Requires less material than tension test Provides actual ultimate strength and yield strength of isotropic materials Provides exemplar fracture surface	Different behavior of materials in tension and compression testing beyond the elastic region Textured materials have significantly different tensile and compressive strength properties
Bend	Quick and easy method to determine ductility of a material or joint Provides demonstrative evidence of substandard performance	Not standardized Relies on visual examination of specimen Requires sufficient sample size to performthe test

from the test may not be exactly the same as the standard test sample, especially ductility. In addition, most available databases will contain limited information on the smaller test samples for comparison.

The second limitation in failure analysis is the direction, or orientation, of the tensile test. As noted previously, almost all materials demonstrate anisotropic behavior in mechanical properties, so the orientation of the tensile test is also important. Unfortunately, depending on the size of the failed hardware, it may not be possible to obtain a tensile sample in the desired orientation.

Uniaxial Compression Testing

Compression loads occur in a wide variety of materials applications, such as steel building structures and concrete bridge supports, as well as in materials processing, such as during the rolling and forging of a billet. Characterizing the material response to these loads requires tests that measure the compressive behavior of the materials. Under certain circumstances, compression testing may also have advantages over other testing methods. Tension testing is by far the most extensively developed and widely used test for material behavior, and it can be used to determine all aspects of the mechanical behavior of a material under tensile loads, including its elastic, yield, and plastic deformation and its fracture properties. However, the extent of deformation in tension testing is limited by necking. To understand the behavior of materials under the large plastic strains during deformation processing, measurements must be made beyond the tensile necking limit. Compression tests and torsion tests are alternative approaches that overcome this limitation.

Furthermore, compression-test specimens are simpler in shape, do not require threads or enlarged ends for gripping, and use less material than tension-test specimens. Therefore, compression tests are often useful for subscale testing and for component testing where tension-test specimens would be difficult to produce. Examples of these applications include through-thickness property measurements in plates and forgings, weld heat-affected zones, and precious metals where small amounts of material are available.

In addition, characterizing the mechanical behavior of anisotropic materials often requires compression testing. For isotropic polycrystalline materials, compressive behavior is correctly assumed to be identical to tensile behavior in terms of elastic and plastic deformation. However, in highly textured materials that deform by twinning, as opposed to dislocation slip, compressive and tensile deformation characteristics differ widely.

Uses and Limitations in Failure Analysis

A uniaxial compression test provides a failure analyst the actual, or typical, mechanical properties and exemplar fracture surface of the material specific to the failure location and load direction. The actual mechanical property information and exemplar fracture surface of the material is critical in the evaluation of the many aspects of the failure analysis, such as comparison to the design specification, verification of heat treatment condition, comparison to the service loads, determination of failure mechanism, and so on.

Unfortunately, as noted in Table 2, there are limitations to uniaxial compression testing in failure analysis. The first limitation in failure analysis is the different behavior of materials in tension and compression testing beyond the elastic region. For isotropic polycrystalline materials, compressive behavior is correctly assumed to be identical to tensile behavior in terms of elastic and plastic deformation. For polycrystalline materials, the bulk elastic and plastic deformation characteristics are generally the same in compression and tension. As a result, the elastic modulus, yield strength, and work-hardening curves will be the same in compression and tension tests. However, the fracture strength, ultimate strength, and ductility depend on localized mechanisms of deformation and fracture and are generally different in tension and compression testing.

The second limitation in failure analysis occurs with textured materials. In highly textured materials that deform by twinning as opposed to dislocation slip, compressive and tensile deformation characteristics differ widely.

Bend Testing

Bend tests are conducted to determine the ductility or strength of a material. Bend tests for ductility differ fundamentally from other mechanical tests in that most mechanical tests are designed to give a quantitative result and have an objective endpoint. In contrast, bending ductility tests give a pass/fail result with a subjective endpoint; the test operator judges whether a surface has undergone cracking.

Test procedures and specimen-preparation methods have evolved without close attention to detail. Therefore, despite the value of the test and its long history of use, there has been minimal standardization. There are, however, two ASTM International standards—E 190 and E 290—that provide guidelines for testing strip, sheet, plate, and weldments (Ref 2, 3).

Tests for determining the bending strength of metals have not been used widely, although the information from such tests is clearly useful. ASTM International E 855 discusses the techniques for determining the bending strength of metal (Ref 4).

Uses and Limitations in Failure Analysis

When a failure analyst is evaluating a weld-related failure, it is useful to understand the ductility of the weld material and heat-affected zone (HAZ). The primary method for assessing the ductility of welds is through a bend test, which is used to validate a weld procedure and qualify individual welders. Indications of brittle fracture associated with a weld can be assessed by using a bend test.

Often, weld-related failures preclude the opportunity to perform bend testing, because the fracture generally passes through the weld, the HAZ, or the base metal adjacent to the weld. Therefore, there is insufficient material to perform a proper test.

Hardness Testing

The term *hardness*, as it is used in industry, may be defined as the ability of a material to resist permanent indentation or deformation when in contact with an indenter under load. Generally, a hardness test consists of pressing an indenter of known geometry and mechanical properties into the test material. The hardness of the material is quantified by using one of a variety of scales that directly or indirectly indicates the contact pressure involved in deforming the test surface. Because the indenter is pressed into the material during testing, hardness is also viewed as the ability of a material to resist compressive loads. The indenter may be spherical (Brinell test and some Rockwell methods), pyramidal (Vickers and Knoop tests), or conical (Rockwell C and N scales). In the Brinell, Vickers, and Knoop tests, the hardness value is the load supported by the unit area of the indentation. In the Rockwell tests, the depth of indentation at a prescribed load is determined and converted to a unitless hardness number.

Hardness, although apparently simple in concept, is a property that represents an effect of complex elastic and plastic stress fields set up in the material being tested. The microscopic events such as dislocation movements and phase transformations that may occur in a material under the indenter should not be expected to exactly repeat themselves for every indentation, even under identical test conditions. Yet, experience has shown that the indentations produced under the same test conditions are macroscopically nearly identical, and measurements of their dimensions yield fairly repeatable hardness numbers for a given material. This observation by James A. Brinell in the case of a spherical indenter led to the introduction of the Brinell hardness test. This was followed by other tests (previously mentioned) with unique advantages over the Brinell indenter.

Hardness testing is perhaps the simplest and least expensive method of mechanically characterizing a material because it does not require elaborate specimen preparation, involves rather inexpensive testing equipment, and is relatively quick. Theoretical and empirical investigations have resulted in fairly accurate quantitative relationships between hardness and other mechanical properties of materials.

Uses and Limitations in Failure Analysis

As described previously, hardness is one of the most used and versatile mechanical testing techniques employed today (2020), and that includes use in failure analysis. Often, failed components or parts of failed components are of insufficient size to perform standard strength testing, so the hardness data are the primary avenue available to the failure analyst. While hardness testing provides a wealth of information, care should be taken to ensure that the data are not used incorrectly, or the failure analyst will draw inappropriate correlations. The advantages and disadvantages of the various types of hardness testing are presented in Tables 3 to 5.

Hardness is probably one of the most misused mechanical testing techniques in the failure analyst's toolbox. While hardness was originally used as a quality-control/assurance metric, empirical data obtained through years of testing have produced a number of conversion tables and charts that are commonly used and used incorrectly.

ASTM International E 140 is an oft-used document that was originally developed from empirical data collated from a number of participating laboratories, manufacturers, raw material producers, and other interested parties (Ref 5). The compiled data were used to produce graphical representations (curves) from which equations describing these curves were derived. These equations were subsequently used to generate the tabular data commonly used to convert one hardness scale to another. As stated in the "Principle of Method of Conversion" in ASTM International E 140, "Indentation hardness is not a single fundamental property but a combination of properties, and the contribution of each to the hardness number varies with the type of test.... Therefore, separate conversion tables are necessary for different materials." The "Significance and Use" section in the standard provides significant qualifiers for the data therein, including repeated statements regarding the approximate nature of the conversion tables and that reliance on the conversions should be avoided whenever possible (Ref 5).

Table 1 (Rockwell C range) and Table 2 (Rockwell B range) in ASTM International E

Table 3 Advantages and disadvantages of macroindentation hardness tests

Test	Advantages	Disadvantages
Rockwell hardness	Quick and easy to perform Data correlate to tensile strength for nonaustenitic steels Able to provide superficial hardness using light loads Correction factor allows for measurement on curved surfaces Portable testers exist Different scales, indenters, and loads allow a wide variety of materials to be tested using a single machine	Test easy to perform incorrectly Data correlate to tensile strength for only a few alloy systems Data do not correlate to ductility
Brinell hardness	Quick and easy to perform Data correlate to tensile strength for nonaustenitic steels Portable testers exist	Test easy to perform incorrectly Data correlate to tensile strength for only a few alloy systems Data do not correlate to ductility
Vickers hardness	Over 5 kgf is independent of force on a homogeneous material Edges of the indentation are usually well defined Indentations are geometrically similar, regardless of size One continuous scale is given for a force Indenter deformation is negligible on hard material	Time-consuming Specimen must be mounted on machine User-measured values lead to variability

Table 4 Advantages and disadvantages of microindentation hardness tests

Test	Advantages	Disadvantages
Vickers hardness	Characterization of surface modification/coating Hardness profiles across weld interfaces Hardness of different phases in same sample	Requires a polished cross section through areas of interest User-measured values lead to variability Hardness value is load-specific Microhardness does not always correlate to bulk hardness
Knoop hardness	Characterization of surface modification/coating Hardness profiles across weld interfaces Hardness of different phases in same sample Shape of indenter allows near-surface measurements	Requires a polished cross section through areas of interest User-measured values lead to variability Hardness value is load-specific Microhardness does not always correlate to bulk hardness
Ultrasonic hardness	Portable Can be used on any surface No load applied to the sample	Difficult to use properly Requires a polished surface

Table 5 Advantages and disadvantages of other indentation hardness tests

Test	Advantages	Disadvantages
Nanoindentation hardness	Provides data on thin coatings, strips, metallized surfaces, etc. Provides data regarding small phases within an alloy	Expensive Small sample size High variability Limited data for reference
Scleroscope hardness	Quick and easy to use Portable Nondestructive Single scale covers entire hardness range	Sensitive to surface features Requires vertical orientation on sample Minimum workpiece weight required
Leeb (Equotip) hardness	Quick and easy to use Portable	Minimum workpiece weight required

140 are the approximate conversion tables for nonaustenitic steels. These data are commonly reproduced in large, poster-sized wall hangings by hardness-testing companies or in small plastic cards used for quick reference. Sometimes these reproductions state that the data are obtained from Tables 1 and 2 of ASTM International E 140; some even state that the data are specific to nonaustenitic steels. However, more commonly, there is no reference at all, or it is merely a footnote, often overlooked or disregarded. Although the application of these conversion tables should be strictly limited to nonaustenitic steels, many users incorrectly and erroneously convert hardness values obtained on other materials with these tables.

Tables 2 and 3 in ASTM International A 370 provide approximate hardness conversion numbers for nonaustenitic steels (converting Rockwell C and Rockwell B scale values to various other scales) (Ref 6). Included in the conversion tables is a column for approximate tensile strength. This column is often included in the aforementioned posters and placards. Again, although these tensile strength values are approximate, based on empirical data collected historically and curve-fit, and specific to nonaustenitic steels, these conversions from hardness to tensile strength are often erroneously applied to various other materials, which can often lead to incorrect conclusions regarding the root cause of failures. As stated in the footnote for Tables 2 and 3, "This table gives the approximate interrelationships of hardness values and approximate tensile strength of steels. It is possible that steels of various compositions and processing histories will deviate in hardness-tensile strength relationship from the data presented in this table.... Where precise conversions are required, they should be developed specially for each steel composition, heat treatment, and part."

In addition, the failure analyst should also consider other limitations to hardness testing, including the appropriateness of averaging data; use of the appropriate hardness test, especially for bulk hardness; accuracy of hardness data; and so on. Hardness is usually used as a correlation to heat treatment condition and/or tensile strength. Therefore, any singular failure of a hardness test indicates an area that does not satisfy a tensile strength requirement. Good hardness-testing practice would require between three and five hardness tests. The hardness data should not be averaged but presented as separate data points, unless otherwise indicated by the controlling specification.

The various hardness tests were designed for specific purposes. The failure analyst must recognize that it is important to use the appropriate hardness test for the appropriate purpose. The most common mistake is to use microhardness testing for bulk material tests. Microhardness testing is sensitive to microstructural variations and may not provide accurate bulk material hardness data. Lastly, a failure analyst must consider the accuracy of a hardness test. Common hardness testing procedure would require that hardness testing be preceded by the use of a hardness calibration block. The accuracy of the hardness test is directly related to the accuracy of the hardness block used, which can range from approximately ±0.5 to ±2.0 in accordance with Table 4 of ASTM International E 18-15 (Ref 7). The calibration block dictates the error band on the test data. The error band is what the failure analyst should consider.

When measuring the hardness of nonhomogeneous microstructures such as cast iron, it is imperative that the indenter be large enough to account for the different phases within the structure. Using techniques with smaller indenters, that is, Rockwell B (with a 3.2 mm, or ⅛ in., diameter ball), will provide false high and/or low readings depending on whether the indentation was coincident with a hard carbide particle or a soft graphite flake or nodule. The 10 mm (0.4 in.) ball used in Brinell hardness testing is appropriate for these types of materials.

Macroindentation Hardness

Almost all indentation hardness testing is done with Brinell, Rockwell, Vickers, and Knoop indenters. These modern methods of indentation testing began with the Brinell test, which was developed circa 1900 when the manufacturing of ball bearings prompted J.A. Brinell in Sweden to use them as indenters. The Brinell test was quickly adopted as an industrial test method soon after its introduction, but several limitations also became apparent. Basic limitations included test duration, the large size of the impressions from the indent, and the fact that high-hardness steels could not be tested with the Brinell method of the early 1900s.

The limitations of the indentation test developed by Brinell prompted the development of other macroindentation hardness tests, such as the Vickers test introduced by R. Smith and G. Sandland in 1925, and the Rockwell test invented by Stanley P. Rockwell in 1919. The Vickers hardness test follows the same principle of the Brinell test; that is, an indenter of definite shape is pressed into the material to be tested, the load removed, the diagonals of the resulting indentation measured, and the hardness number calculated by dividing the load by the surface area of indentation. The principal difference is that the Vickers test uses a pyramid-shaped diamond indenter that allows testing of harder materials, such as high-strength steels.

The Rockwell hardness test differs from Brinell hardness testing in that the hardness is determined by the depth of indentation made by a constant load impressed upon an indenter. Rockwell hardness testing is the most widely used method for determining hardness, primarily because the Rockwell test is fast, simple to perform, and does not require highly skilled operators. By use of different loads (force) and indenters, Rockwell hardness testing can determine the hardness of most metals and alloys, ranging from the softest bearing materials to the hardest steels.

Microindentation Hardness

In microindentation hardness testing (microhardness testing), a diamond indenter of specific geometry is impressed into the surface of the test specimen using a known applied force of 100 to 1000 gf in the United States and 200 to 3000 gf in Europe. Forces smaller than 200 gf generally produce hardness numbers that are different from those determined from tests conducted with forces $\geq$200 gf.

The hardness number is based on measurements made of the pyramidal indent formed in the surface of the test specimen. For the Vickers test, the indenter is symmetric; thus, both diagonals are measured and the average value is used to compute the Vickers hardness (HV). The hardness number is actually based on the surface area of the indent itself divided by the applied force, giving hardness units of kgf/mm^2. In the Knoop test, the indenter is elongated in one direction; thus, only the long diagonal is measured and the Knoop hardness (HK) is calculated based on the projected area of the indent divided by the applied force, also giving test units of kgf/mm^2. In practice, the test units kgf/mm^2 (or $gf/\mu m^2$) are not reported with the hardness value, but the load is in kilograms; for example, a reading obtained using a Knoop indenter and 500 g load would be expressed as $HK_{0.5}$.

Other Hardness Tests

Other hardness tests, such as nanoindentation hardness, Scleroscope hardness, Leeb (Equotip) hardness, and scratch hardness, can be helpful in specific applications and are used to varying degrees. Each technique provides advantages not necessarily available with other techniques.

Nanoindentation hardness is a relatively new method (also referred to as instrumented indentation hardness) and is used to characterize material mechanical properties on a very small scale, with features less than 100 nm across. It is used in conjunction with atomic force microscopy. There is currently debate regarding the reliability and efficacy of the data obtained using this technique; thus, great care should be taken with the use of these data.

The Scleroscope (Instron Corporation, Canton, MA) dynamic hardness tester was invented by Albert F. Shore in 1907 and was the first commercially available metallurgical hardness tester produced in the United States. While Scleroscopes are not currently manufactured in the United States, the unit is still used frequently for testing very large specimens such as forged steel or wrought alloy steel rolls. In this procedure, a diamond-tipped hammer is dropped from a fixed height onto the surface of the material being tested. The height of rebound of the hammer is a measure of the hardness of the metal.

Leeb testers (Equotip) are portable hardness testers that operate on a dynamic rebound principle similar to the Scleroscope. An impact device is propelled into the sample using a spring for the initial energy. The impact device travels a short distance until it contacts the sample. A small indent is formed, and the impact device rebounds away from the test surface according to the hardness and elasticity of the material. An electronic induction coil measures the velocity of the impact device before and after it contacts the sample. The portable nature of these testers allows for fast, reliable hardness testing in the field. One of the limitations of the technique is that a minimum mass and thickness is required for accurate measurement.

Impact Toughness Test

Toughness is defined as the ability of a material to absorb energy. It is usually characterized by the area under a stress-strain curve for a smooth (unnotched) tension specimen loaded slowly and under controlled conditions to fracture. Notch toughness represents the ability of a material to absorb energy and is determined under impact loading in the presence of a notch. Notch toughness is measured by using a variety of specimens, such as the Charpy V-notch impact specimen, Izod impact sample, drop weight impact test, dynamic-tear specimen, and plane-strain fracture toughness specimens under static loading (K_{Ic}) and impact loading (K_{Id}).

Traditionally, the notch toughness characteristics of low- and intermediate-strength steels have been described in terms of the transition from ductile to brittle behavior as test temperature decreases. Most structural steels can fail in either a ductile or a brittle manner depending on several conditions, such as microstructure, temperature, loading rate, and constraint.

The most widely used specimen for characterizing the ductile-to-brittle transition behavior of steels has been the Charpy V-notch impact specimen, described in ASTM International E 23 (Ref 8). These specimens may be tested at different temperatures, and the impact notch toughness at each test temperature may be determined from the energy absorbed during fracture, the percent shear (fibrous) (versus cleavage or flat) fracture on the fracture surface, or the change in width of the specimen (lateral expansion).

The impact toughness test can also be used to determine the effect on toughness by microstructural alteration in a material or surface alteration/contamination of the material.

An example of the drop weight impact test is ASTM International E 208 (Ref 9). The ASTM International E 208 drop weight test is used to determine the nil-ductility transition (NDT) temperature of ferritic steels 15.9 mm (5/8 in.) thick or thicker. The NDT temperature is the temperature at which the fracture mode of the ferritic steel changes from ductile to brittle. At temperatures above the NDT, the ferritic steel will deform in a ductile manner before fracturing when tested. At temperatures lower than the NDT, the ferritic steel will fail in a brittle manner when tested.

Uses and Limitations in Failure Analysis

An impact toughness test provides a failure analyst the actual, or typical, mechanical properties and exemplar fracture surface of the material as a second variable is altered. The second variable is usually temperature but could be microstructure, surface alteration/contamination, and so on. The actual mechanical property information and exemplar fracture surface of the material are critical in the evaluation of the many aspects of the failure analysis, such as comparison to the design specification, verification of the heat treatment condition, comparison to the service temperature or environment, determination of the failure mechanism, and so on.

Unfortunately, as noted in Table 6, there are limitations to impact toughness testing in failure analysis. The first limitation is the amount of material required for the test. The impact test samples are small, approximately 10 by 10 by 55 mm (0.4 by 0.4 by 2.2 in.) for a Charpy test sample, but because there are usually multiple samples required for the testing, a larger amount of material is necessary. For example, if four temperatures are required to be evaluated and three samples are done at each temperature, then a total of 12 test samples are required. This example leads into the second limitation in failure analysis: the test variability of impact testing. It is always recommended to do at least three impact tests

Table 6 Advantages and disadvantages of impact toughness tests

Test	Advantages	Disadvantages
Charpy impact	Higher strain rate than tensile test Quick and easy to perform Good for comparison of material vs. temperature or potential microstructure variation Smaller sample size than a tensile test Provides exemplar fracture surface	Requires sufficient material to produce a standard specimen Multiple tests required due to test variability Orientation-specific depending on anisotropy of the microstructure
Izod impact	Higher strain rate than tensile test Quick and easy to perform Good for comparison of material vs. temperature or potential microstructure variation Smaller sample size than a tensile test Provides exemplar fracture surface	Requires sufficient material to produce a standard specimen Multiple tests required due to test variability Orientation-specific depending on anisotropy of the microstructure
Drop weight impact	Specimens can be full thickness; results more easily correlated to the actual	Greater amounts of material; test machines are correspondingly larger

for each condition, due to the variability of impact testing.

The third limitation in failure analysis is the direction, or orientation, of the impact test samples. Because almost all materials demonstrate anisotropic behavior in mechanical properties, the orientation of the impact test is important. Unfortunately, depending on the size of the failed hardware, it may not be possible to obtain the impact samples in the desired orientation.

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- George E. Dieter, "Mechanical Behavior Under Tensile and Compressive Loads"
- John M. (Tim) Holt, "Uniaxial Tension Testing"
- "Impact Toughness Testing"
- Howard A. Kuhn, "Uniaxial Compression Testing"
- Gopal Revankar, "Introduction to Hardness Testing"
- Eugene Shapiro, "Bend Testing"
- Edward L. Tobolski, "Miscellaneous Hardness Tests"
- Edward L. Tobolski and Andrew Fee, "Macroindentation Hardness Testing"
- George F. Vander Voort, "Microindentation Hardness Testing"

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