Hardness Testing

To create effective tools, people need to find materials harder than the substance they wish to work on.

The direct measurement of hardness has been attempted since before the Machine Age. Evaluations of a material's relative resistance to deformation were noted in early treatises, such as the description of a file test performed in 1640, a test which is still used today.

Over time, a variety of hardness tests have been developed to quickly evaluate and compare materials. Hardness, however, is not a fundamental property like tensile strength or elastic modulus, but rather a derived quantity based on the complicated response of a material to a specific test. Each hardness system, therefore, measures a slightly different set of material traits.

The earliest method for measuring hardness involved the use of a scratch test, in which a tester determines a material's resistance to scratching or abrasion by a sequence of standard objects. This system was first codified in Germany by the mineralogist Friedrich Mohs (1773–1839). In 1812 Mohs assigned a numerical value from 1 to 10 to a series of common minerals and published his scale in 1822 in *Grundriss der Mineralogie.*

For the softest mineral in his scale, talc, Mohs assigned the number 1. Gypsum received a 2; calcite, 3; fluorite, 4; apatite, 5; orthoclase feldspar, 6; quartz, 7; topaz, 8; corundum, 9; and diamond, 10.

Mohs was most interested in using his scale to identify unknown minerals he found in the field. Since harder minerals scratch softer ones, a mineralogist, by bringing along samples of his 10 standard substances, could readily position unknown samples between minerals on the standard scale. As useful additions to the hardness scale, Mohs included the human fingernail (slightly greater than 2), the copper penny (3), the blade of a pocketknife (5+), window glass (5.5), and a steel file (6.5). So, with just a few simple items, a field mineralogist could make a broad measurement in only a few moments.

Minerals of hardness 6 or greater cannot be scratched with a knife, but they can scratch glass. Minerals with a Mohs number of 4 can be scratched easily with a pocketknife while those with a number of 5 are difficult to scratch. Minerals of hardness 1 have a slippery feel; those with a number 2 can be scratched with a fingernail. Samples with a Mohs number of 3

https://doi.org/10.1557/S0883769400048491 Published online by Cambridge University Press

are easily cut with a knife blade.

The Mohs test needed to be applied carefully, however, because many minerals contain surface impurities, and testers must be sure they are working on the actual surface rather than on a crust. Also, if the unknown sample is fine-grained or friable, the scratch test may only loosen grains from the aggregate without testing the mineral itself.

For all its usefulness, the Mohs scale is arbitrary and nonlinear. The physical hardness of diamond, for example, with a Mohs number of 10, is many times higher than corundum, the preceding standard mineral with a number 9. (See the Historical Notes on diamonds and abrasives in the *MRS Bulletin*, August and September 1994.)

When synthetic abrasive materials become widely available at the beginning of this century, R.R. Ridgway and his coworkers, finding they needed more numbers at the high end of the scale, modified Mohs' scheme. C.E. Wooddell measured how much various minerals resisted wearing down with diamond abrasives, which allowed a finer categorization between the Mohs numbers of 9 and 10. Ridgway arbitrarily shifted the value of diamond to 15 on the scale instead of 10, which allowed them to assign hardness numbers of 12 to fused alumina, 13 to silicon carbide, and 14 to boron carbide.

In 1900, J.A. Brinell offered a method for an even more precise evaluation of hardness, particularly of metals. As proposed in his French publication, *II Congres Int. des Methodes d' Essai*, the Brinell method uses a hardened 10-mm-diameter steel ball in contact with the plane surface of metal; a load of 3000 kg is applied for 10 seconds and then removed. The diameter of the resulting impression is measured, which allows calculation of the spherical area of the indentation. The Brinell hardness number is the load in kilograms divided by the indentation area in square millimeters.

The Brinell test, however, was useful only for metals softer than a steel indenter. Metals used in tools often exceed this hardness. In about 1920, the metallurgist Stanley P. Rockwell introduced a similar test using instead a conical diamond indenter with a spherical point.

The mechanical apparatus for the Rockwell test directly measures the difference in impressions made by a large load and a smaller load, which allows the hardness number to be read directly from a dial on the machine, rather than requiring further inspection and calculation.

Another versatile indentation test, the Vickers method, uses a pyramidal diamond that is pushed into the material being tested for 15 seconds under a specified load. The indenter is removed and the resulting indentation is measured under a microscope. (The actual indentation hardness is defined as the ratio of the applied load to the projected surface area of the indentation produced.) This method was originally proposed in the April 25, 1924 issue of *Engineering* by R.L. Smith and G.E. Sandland in their paper, "Accurate Determination of the Hardness of Metals."

In July 1939, in "A Sensitive Pyramidal-Diamond Tool for Indentation Measurements," F. Knoop, C.G. Peters, and W.B. Emerson proposed using an *elongated* diamond-shaped indenter since some materials, such as glass and crystal, will crack under application of the diamond indenters used in other techniques. The special shape of the Knoop indenter allows testers to measure brittle materials—including glass and even diamonds—without cracking or spalling either the test piece or the indenter itself.

The various techniques developed to measure hardness are applicable over a wide range of materials and accuracies, from rapid and crude estimates to extremely sophisticated measurements. New materials and industrial processes with precise tolerances require even further refinements of these techniques.

One of the newer methods involves the use of a nanoindenter, which employs a three-sided pyramidal diamond indenter (the Knoop and Vickers tests each use a four-sided diamond tip). The nanoindenter tip more accurately comes to a single point, which is particularly important for very small indents. The nanoindenter tip displacement is continuously monitored as the load is applied. The continuous monitoring allows one to plot the penetration depth versus load, revealing elastic and plastic behavior of a material without directly imaging the indent.

While the Mohs test is still used by rock hunters and amateur mineralogists, exotic new materials such as aerogels and extremely hard advanced materials may require even more unusual test methods or indenters.

KEVIN J. ANDERSON

LIBRARY

Mathematical Modelling of Weld Phenomena

Edited by H. Cerjak and K.E Easterling (The Institute of Materials, 1993, 369 pages).

ISBN: 0-901716-16-2

The 15 chapters in this book, authored by experts from 10 different countries, constitute the proceedings of a conference in Graz, April 1991, organized by the International Institute of Welding. The actual scope of the work is rather more narrow than the title indicates. The only groups of welding processes considered are arc welds and laser-beam welds (one chapter), and the only materials considered are steels (12 chapters) and aluminum (2 chapters). The phenomena described include heat flow, melt turbulence, solidification kinetics, and solid-state transformations; residual stress development is not treated. The editors attempt not only to model the physics of these individual processes, but also, by integrating all the relevant processes, to predict microstructures of weld metal and heat-affected-zone and, hence, their mechanical properties. The final two chapters of the book categorize and describe some of the more than 100 available software packages relating to weldability, design calculations, defect analysis, expert systems, and other topics.

The overall picture presented is that mathematical modeling of arc welding of steels has become very sophisticated and remarkably successful in reproducing real behaviors. The welding engineer can therefore use these procedures with confidence to define welding conditions, select filler metals, specify heat treatments, or select new compositions to meet a defined need. The principal deficiency at present is the lack of data on the relevant physical properties and their temperature dependences. Even in the absence of such data, useful results can still be obtained in many cases by treating these values in the calculations as adjustable parameters which can later be checked for plausibility and conformance with the few numbers at hand.

The book is provided with an adequate index. It is regrettable, however, that the editors did not include a list of acronyms and their expansions. While most metallurgists and welding engineers might easily recall TTT, HAZ, and HSLA, many other more arcane shorthand notations, such as KS/NW, CTOD, PWHT, and EELS, are nowhere defined in the text and can therefore inhibit ready understanding