THE SCIENCE OF HARDNESS TESTING AND ITS RESEARCH APPLICATIONS

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The Science of Hardness Testing and Its Research Applications

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Edited by
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Preface

Hardness must surely be one of the properties of materials first subjected by man to careful intercomparison and semiquantitative appraisal. Even before the age of metals and ceramics, men were choosing soapstone for fashioning utensils and ornaments because its softness made it readily cut and flint for knives, tools and weapons because its hardness meant strength and ability to retain an edge. Exercise of such choices from naturally occurring materials whose color, density and other more obvious attributes were frequently very similar implies a conscious testing of hardness by scratching, nicking or other means. Yet, tens of thousands of years elapsed before serious attempts were made to develop a scale of hardness values. One of the first such was recorded by Reaumur in his 1722 memoir, where he described the scratching of metals by a series of minerals, thus anticipating Mohs by nearly a century.

Today, despite a proliferation of highly sophisticated techniques for measuring the mechanical properties of materials, hardness tests are used more widely than ever. Why should this be? It is simply that the attractions of the test to neolithic man—simplicity, convenience, nondestructiveness, and direct correlation with service performance—are no less pertinent to his descendant living in today's space age. And there are other reasons why the hardness test retains its place in the materials scientist's armamentarium. Hardness tests are readily adaptable to testing under special conditions of temperature, pressure and chemical environment. Moreover, the possibilities of greatly reducing the scale of the test open up many opportunities of using (in Gilman's words) hardness as a strength microprobe. It may be applied to small samples, it can assess chemical and structural heterogeneities such as diffusion gradients, precipitates, eutectics, dendrites and grain boundaries, and it can readily explore the influence of fields, radiation or environment on mechanical behavior of surfaces.

Notwithstanding these attractions and about 300 years of continued scientific interest in the property and technique, hardness is still poorly understood. This is so because it is not a single property but rather a whole complex of mechanical properties and at the same time a measure of the intrinsic bonding of the material. For the

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foregoing reasons, hardness measurements continue to be widely used in both technological and scientific work and the variety and sophistication of the problems to which they are applied grow daily. Recognizing this, the editors organized a group of papers for presentation at the 1971 Materials Engineering Congress in Detroit. The papers presented there were extended in their written form, and supplemented by discussion and a few short contributions that for various reasons were not available in Detroit, to constitute the present volume.

The last previous volume published by ASM treating the subject of hardness was Williams' monograph that appeared in 1942 and contained nearly 2000 references to the prior literature. Since that time, a number of other treatises on hardness have been published elsewhere, among the more notable of these being Tabor (1951), Mott (1956), Bückle's thesis (1960), and Glazov and Vigdorovich (1971). Each of the latter has its own particular slant and appeal but none makes a serious attempt to review the whole of the literature. Recognizing the current resurgence of interest in hardness properties and techniques by the scientific community, the editors determined that a comprehensive review and assessment of progress in understanding of the hardness test and of its research applications was in order. It was decided to supplement a broad coverage of this field in a series of eight reviews with a selection of some current research papers. This book, resulting from that plan, contains contributions from France, West Germany, Canada, Australia, the United Kingdom, and the USSR as well as from our own country, properly reflecting the earlier and more intensive interest in the technique abroad than here. Almost 1000 literature references appear.

The book presents many new and interesting results, only a few of which can be singled out for special mention. Weiler demonstrates the futility of the hope for a complete and accurate intraconvertibility of hardness scales by his extensive data sets derived from several different testing techniques. Böklen shows that it is possible to measure ductility from cone indentation tests—a possible boon when the necessity is at hand for determining this parameter for a number of small or broken pieces. Several authors report on the indentation deformation of very hard materials, including diamond, and are able to adduce evidence that this is indeed true plastic flow. Gilman, by experiment and calculation, calls attention to the very real possibility of crystallographic transformation under the very high pressures produced under a loaded indenter. He also proposes a reasonable explanation for the anomalous hardness/yield-strength ratio of the NaCl-structure compounds as contrasted to the face-centered-cubic metals, reported by Westbrook fifteen years ago. Atkins shows that

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both changes in operative slip systems with temperature and deviations from stoichiometry significantly affect the temperature dependence of hardness of several technologically important materials. A group of six papers presents the improvements in our ability to assess, from hardness measurements, the anisotropic behavior of materials that have been achieved since the classic paper of Daniels and Dunn in 1949. Finally, new data on both room- and elevated-temperature hardness are given for cubic boron nitride, the only close rival to diamond in hardness, and generally its superior in terms of chemical reactivity. The microhardness of zinc is found by Latanision to be dependent on applied potential.

Review of the contents of the book makes it clear that there are many questions posed by results reported or reviewed here that will require further research for their elucidation. Gane's famous experiment with an ultra-microindenter in the electron microscope has no accepted explanation. Is it a matter of contaminant film lubrication, siting between pre-existent defects in the sample, or the small size of the dislocation loops generated that gives rise to the high apparent-hardness values? Certain materials, for example hafnium carbide, quartz, orthoclase and cubic boron nitride, appear to fall anomalously on empirical plots of hardness vs energy per unit volume or of hardness vs bulk modulus. Is this because of poor hardness data, poor energy or modulus data, or because the attempted correlation is itself too simplistic? Indentation creep has been known for some time in metals at high temperatures, or for light loads and active environments, in nonmetals at low temperatures. Chen and Hendrickson show indentation creep in silver at low temperatures and light loads for which there is yet no complete explanation, and Walker finds opposite effects for polar solvents at high loads relative to low loads. Photomechanical and electromechanical effects have been observed, especially in semi-conductors, by many different investigators. No satisfactory model has yet emerged, nor has an explanation as to why some workers have difficulty in reproducing the phenomena. Grain-boundary and surface hardening have been observed in a wide variety of materials and have been shown to be associated with solute and vacancy gradients. Yet, a detailed model of how such marked changes in hardness can arise still eludes us. Similarly, environmental effects on surface hardness are almost certainly due to an enforced redistribution of charge carriers in the near-surface region, but detailed models to account for the similar effects in structurally dissimilar glasses and crystals are still lacking.

It is to be hoped that readers will find this book a convenient summary and guide to the literature, as well as a stimulant to the

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investigation of the material behaviors fundamental to the hardness test itself and of the many fascinating scientific problems to which it may be applied.

The editors wish to thank the individual authors for their cooperation and forebearance during the long gestation of this volume and their secretaries, Mrs. LaVerne Phan and Mrs. Sharon New, for help in many, many ways in seeing the project through to completion, and to acknowledge the assistance of the late Dr. Taylor Lyman and Mrs. Helen Waldorf of the ASM staff during publication.

Schenectady, N.Y. J. H. WESTBROOK and H. CONRAD
Louisville, Ky. *Symposium Coordinators and Editors*

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Section I. Fundamental Basis of the Hardness Test

Chapter 1

The Fundamental Basis of the Hardness Test

M. C. SHAW

Hardness is a term having a different meaning to different people. It is resistance to penetration to a metallurgist, resistance to wear to a lubrication engineer, a measure of flow stress to a design engineer, resistance to scratching to a mineralogist, and resistance to cutting to a machinist. While these several actions appear to differ greatly in character, they are all related to the plastic flow stress of the material (Y).

The wide variety of hardness test procedures that have been used may be classified as follows:

1 **Static indentation tests,** in which a ball, cone or pyramid is forced into a surface and the load per unit area of impression is taken as the measure of hardness. The Brinell, Vickers, Rockwell, Monotron and Knoop tests are of this type.

2 **Scratch tests,** in which we merely observed whether one material is capable of scratching another. The Mohs and file hardness tests are of this type.

3 **Plowing tests,** in which a blunt element (usually diamond) is moved across a surface under controlled conditions of load and geometry and the width of the groove is the measure of hardness. The Bierbaum test is of this type.

4 **Rebound tests,** in which an object of standard mass and dimensions is bounced from the test surface and the height of rebound is taken as the measure of hardness. The Shore Scleroscope is an instrument of this type.

5 **Damping tests,** in which the change in amplitude of a pendulum having a hard pivot resting on the test surface is the measure of hardness. The Herbert pendulum test is of this type.

6 **Cutting tests,** in which a sharp tool of given geometry is caused to remove a chip of standard dimensions.

7 **Abrasion tests,** in which a specimen is loaded against a rotating disk and the rate of wear is taken as a measure of hardness.

8 **Erosion tests,** in which sand or abrasive grain is caused to impinge upon the test surface under standard conditions and loss of material in a given time is taken as the measure of hardness. Hardness of grinding wheels is measured thus.

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The equipment and detailed test conditions for most of the hardness tests in use today may be found in references 1 to 4. In this paper some fundamental aspects of the static indentation hardness test are considered.

When a cylindrical specimen having a length-to-diameter ratio of about two is loaded between flat, parallel surfaces (Fig. 1a), the mean stress at which the specimen becomes fully plastic is referred to as

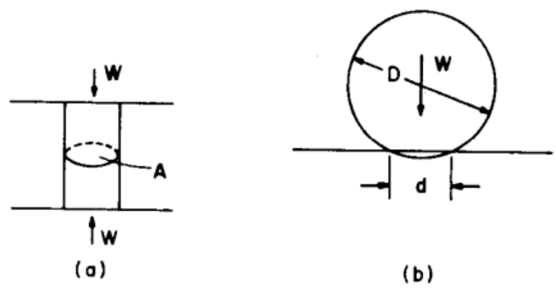

Fig. 1. Comparison of (a) uniaxial compression test and (b) Brinell hardness test.

Fig. 2. (a) Vickers and (b) Knoop hardness indenters.

the uniaxial flow stress (Y). If a sphere is pressed into an extensive flat surface until a plastic dent is produced (Fig. 1b), the mean stress on the dent is found to be about $3Y$ and this mean stress is referred to as hardness.

In the Brinell test (5), the area used to compute the mean stress is the contact area (A_c) rather than the area in the plane of the surface (A) and the Brinell hardness is

$$H_B = \frac{W}{A_c} = \frac{2W}{\pi D[D - \sqrt{D^2 - d^2}]} \qquad (1)$$

where W is the maximum applied load, D is the diameter of the sphere, and d is the diameter of the dent measured in the plane of the original surface.

To obtain representative values of hardness, it is important that:

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1 The load be adjusted so that d/D is between 0.3 and 0.5.

2 The load be maintained for at least 30 sec.

3 The hardness of the indenter be at least 2-1/2 times the hardness of the specimen.

4 The specimen extend several times the diameter of the impression (d) below and to the sides of the indentation.

The Meyer (6) hardness (H_M) is based upon the area projected into the plane of the surface (A) and hence is a simpler concept.

$$H_M = \frac{W}{A} = \frac{4W}{\pi d^2} \tag{2}$$

Smith and Sandland (7) proposed that a pyramid be substituted for a ball in order to provide geometrical similitude under different values of load (Fig. 2a). The apex of their indenter was 136° since this is the angle subtended by the tangents of a sphere when $d/D = 0.375$. The Vickers hardness (H_V) is obtained by dividing the load by the contact area (A_c).

$$H_V = \frac{W}{A_c} = \frac{0.2\,W}{d_1^{\,2} \sin\left(\frac{136}{2}\right)} \tag{3}$$

where d_1 is the mean diagonal length of impression at the surface.

The Knoop (8) hardness indenter has the geometry shown in Fig. 2(b) and provides a diagonal impression that is seven times as long in one direction as in the other direction. This indenter is more blunt than the Vickers and hence gives a shallower impression, a characteristic of importance in the microhardness testing of brittle materials or thin specimens. Unlike Brinell and Vickers hardnesses, the Knoop hardness is expressed in terms of the projected area, rather than the contact area of the indentation:

$$H_K = \frac{W}{A_c} = \frac{2W}{d^2\left(\cot\frac{172.5}{2} + \tan\frac{130}{2}\right)} \tag{4}$$

where d is the length of the long diagonal.

The hardness values obtained by any of these methods may be expressed as CY, where C is termed the constraint factor and Y is the uniaxial flow stress. The constraint factor C depends upon the geometry of the indenter, and other items to be mentioned later, but is approximately three for all of the indenters considered, since

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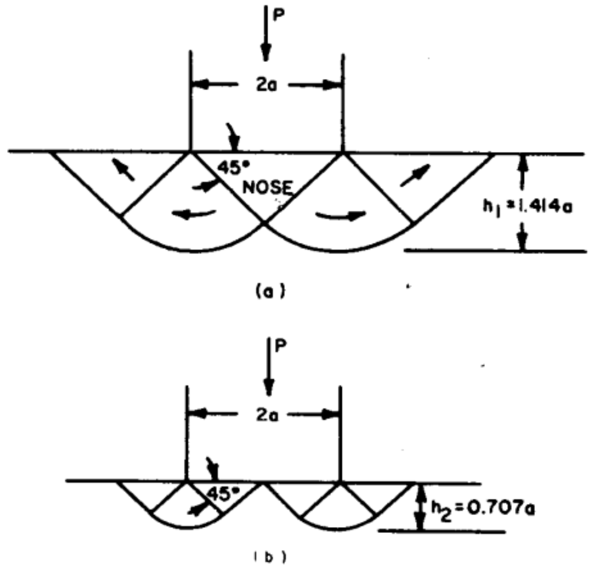

Fig. 3. Slip-line field solutions for a flat two-dimensional punch (a) due to Prandtl (9) and (b) due to Hill (10).

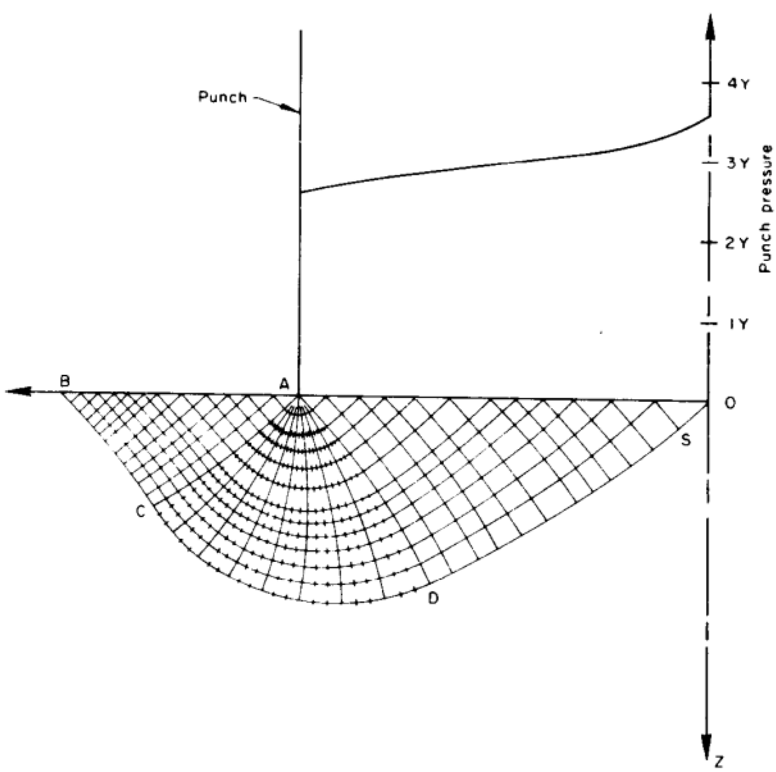

Fig. 4. Slip-line field solution for an axisymmetric flat punch due to Shield (11).

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