The contributions of David Tabor to the science of indentation hardness

Ian M. Hutchings[a)]
Institute for Manufacturing, Department of Engineering, University of Cambridge,
Cambridge CB2 1RX, United Kingdom

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Tabor's book *The Hardness of Metals*, published in 1951, has had a major influence on the subject of indentation hardness and is by far the most widely cited source in this area. Although hardness testing was widely used for practical purposes in the first half of the 20th century, its use was generally based on little scientific understanding. The history of indentation hardness testing up to that point is reviewed, and Tabor's contribution is appraised in this context.

I. INTRODUCTION

Professor David Tabor (Fig. 1), who died in November 2005, was one of the founding fathers of the science of tribology, and was renowned for his contributions to the understanding of friction and boundary lubrication. However, his reputation is just as great for his work on the science of indentation hardness, and that is the topic of the present review.

Tabor was born in London on October 23, 1913, to parents who had emigrated from Russia.[1,2] After undergraduate study at the University of London (Imperial College), he moved to Cambridge in 1936 to undertake research under the supervision of Philip Bowden in the Department of Chemistry. Tabor's collaboration with Bowden lasted until the latter's death in 1968. Their first joint publication[3] in 1939 discussed the area of contact between surfaces, and it established the crucial point that the real area was generally much smaller than the apparent area. This notion was a major theme in much of their subsequent work. At the outbreak of World War II, Bowden, who was Australian and visiting his home country at the time, was persuaded by the Australian Government to set up a research group at Melbourne University to work on the practical problems of lubricants and bearings. Tabor joined the new laboratory in 1940, and he briefly became its head in 1945 to 1946 when Bowden returned to Cambridge. At that point Tabor, at Bowden's behest, conceived the name 'tribophysics' to describe the activities and interests of the group. The Tribophysics Section, becoming the CSIRO Division of Tribophysics in 1948, thrived until 1978 when its name was changed to Division of Materials Science.[4] Tabor rejoined Bowden in Cambridge in 1946, and remained in Cambridge for the rest of his life.

The research group in the University of Cambridge, founded by Bowden and led by Tabor from 1968 until his official retirement in 1981, eventually moved from the Department of Physical Chemistry to the Department of Physics (the Cavendish Laboratory) and changed its name several times. At one point it was named 'Physics of Rubbing Solids' and at another 'Surface Physics'.

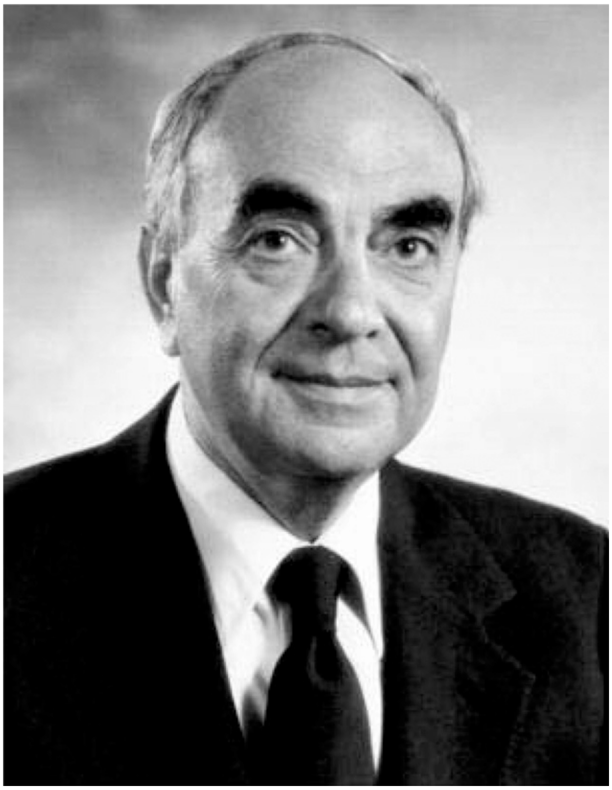

FIG. 1. David Tabor: 1913–2005.

[a)]Address all correspondence to this author.
e-mail: imh2@cam.ac.uk

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However, for much of its existence, it was named ‘Physics and Chemistry of Solids’ and known by the abbreviation ‘PCS’. Despite its changes of name and host department, the aim of the research pursued by Tabor and his group remained constant: to generate a deeper understanding of the physical sciences relevant to problems related to solid surfaces and their interfaces. A central theme was what is now known as tribology, although the group made significant contributions in other areas as well. In particular, Tabor’s work on indentation hardness made a strong and lasting impact on the field. To understand the reasons for this, we shall first examine the position of the indentation hardness test in the first half of the 20th century and then review Tabor’s own contributions. Although the term ‘hardness’ can have various meanings in different contexts, for example implying resistance to elastic deformation in the case of elastomeric materials or resistance to groove formation in scratching, we shall focus here on the normal indentation of materials such as metals, ceramics, or glasses for which plastic flow accounts for a large proportion of the deformation.

II. INDENTATION HARDNESS BEFORE 1950

Although the concept of a mechanical test for metals based on forcing a strong indenter into a plane surface dates back at least 150 years,[5] the modern interpretation of the hardness of a metal as the pressure resisting plastic indentation by a comparatively strong and stiff indenter of well defined geometry originated in 1900 with the work of Brinell.[6,7] The technical manager of a Swedish iron works, Brinell devised the essentials of the method, which is now named after him. In the Brinell test a hard ball of diameter D, originally of hardened steel but later of cemented tungsten carbide, is pressed under a load W into the plane surface under test [Fig. 2(a)]. After removal of the load, the chordal diameter d of the resulting indentation is measured, and the Brinell hardness H_B is defined as the load W divided by the surface area of the spherical cap formed by the indentation:

$$H_\mathrm{B} = \frac{2W}{\pi D^2\left[1 - \sqrt{1-(d/D)^2}\right]} \quad . \tag{1}$$

The Meyer hardness H_M, first defined in 1908,[8] is determined by ball indentation in exactly the same way, but it is defined as the load divided by the projected area of the indentation, so that

$$H_\mathrm{M} = \frac{4W}{\pi d^2} \quad . \tag{2}$$

The Vickers test was first described in 1922,[9] and was commercialized by the Firth-Vickers company. It uses a diamond indenter in the form of a square-based pyramid, with an angle of 136° between the faces, as shown in Fig. 2(b). The indentation intersects the surface in a square with diagonal length d_v, and, as in the Brinell case, the hardness is defined as the load divided by the surface area of the indentation, so that

$$H_\mathrm{V} = \frac{1.854W}{d_\mathrm{V}^2} \quad . \tag{3}$$

All of these tests yield values of hardness with the dimensions of stress, although the numerical value of

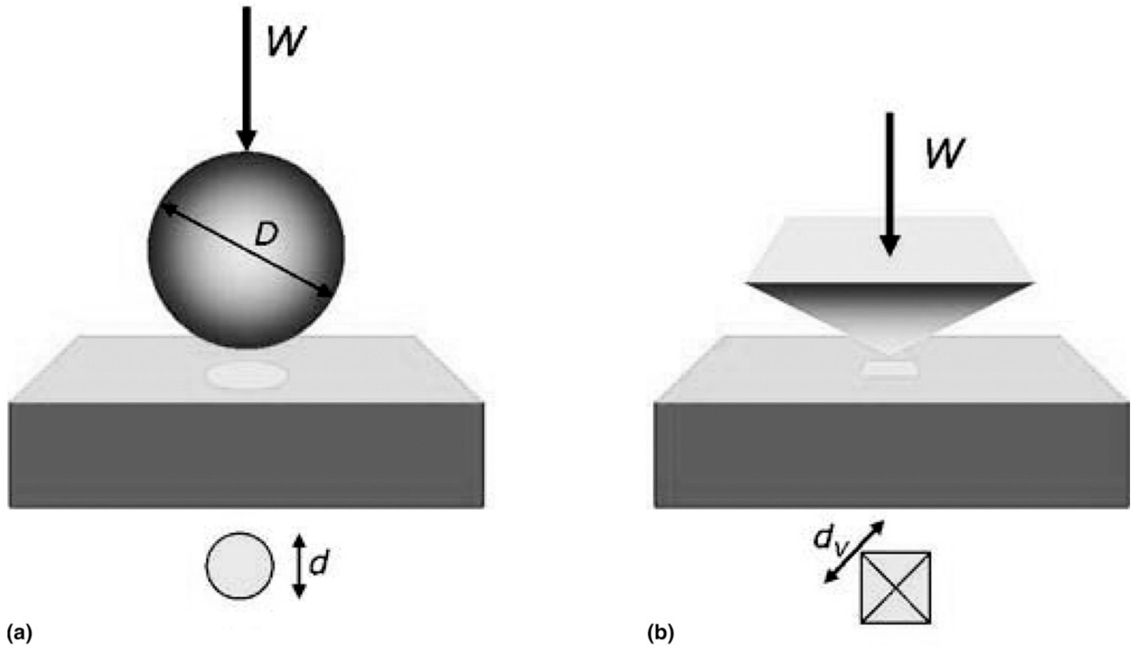

FIG. 2. Commonly used geometries for indentation tests: (a) spherical indenter (Brinell and Meyer); and (b) diamond pyramid (Vickers).

H_B or H_V with W expressed in kg force and the area in mm^2 was usually quoted as a 'hardness number'. These methods, as originally conceived, involved optical microscopy and some degree of operator skill to determine the size of the indentation. In contrast, the Rockwell test,[10] for which a patent was filed in 1914[11] but which was first used commercially in the early 1920s, was more suited to automated use by less-skilled labor. In this test, the dimensionless Rockwell number H_R is derived from the depth of the indentation as measured with the indenter still under load. Several different Rockwell scales were defined, each with its own indenter geometry and maximum load, and each appropriate for the testing of metals with a particular range of hardness. The Rockwell C scale, for example, which is used for heat-treated steels, is based on the application of a major load of 150 kg force (after a minor preload of 10 kgf) to a conical diamond indenter (a Brale indenter), which has an included angle of 120° and a spherical tip with a radius of curvature of 0.2 mm.

The Brinell, Vickers, and Rockwell methods were widely used in the metallurgical and engineering industries in the early part of the 20th century, where they had originated, as quality control measurements and as a means of specifying the mechanical properties of metallic components. The rapid and widespread industrial adoption of these indentation tests, and of other hardness tests that have not survived in use for various reasons, was linked to the development of industrial mass production methods; they were particularly valuable in monitoring the heat treatment and mechanical working of steels and strong nonferrous alloys, which found increasingly demanding uses in the rapidly developing automotive, aircraft, and armaments industries. The munitions industries were particularly influential in the development of the Brinell test during the first World War.[12] Indentation tests offered simplicity and speed compared with conventional tensile testing, requiring access only to a flat surface of a sample or component rather than the fabrication of special specimens with tightly controlled dimensions. Furthermore, several indentation tests could be quickly performed on a small area; they were capable of detecting variations in properties over small distances; and because they are essentially nondestructive, a selection or indeed all of the products from a process could be tested to assure their quality.

The level of interest in indentation hardness testing for industrial purposes is reflected in the number of books on the subject published between 1930 and 1950. The most significant of these were those by O'Neill,[12] Lea,[13] Späth,[14] Williams,[15] and Lysaght.[16] All of these volumes provide comprehensive practical guidance on the various methods by which hardness testing could be performed, but they vary in the extent of their discussion, and understanding, of the underlying scientific basis for these tests. Despite the evident interest in the subject and the large number of research publications devoted to hardness (O'Neill listed more than 400 references, and Williams listed more than 1800 references), there was much confusion over what method should be used as a hardness test. Williams[15] described a wide range of different methods of measuring 'hardness', including tests based on penetration (indentation), scratching, rebound, machinability, yield point, magnetic properties, and electrical properties. Tuckerman from the U.S. National Bureau of Standards, later to become Chief of Engineering, noted in 1925 that hardness was seen as 'a hazily conceived conglomeration or aggregate of properties of a material, more or less related to each other',[17] and this view was repeated by Lysaght in 1949.[16] However, it should be borne in mind that at this point, scientific understanding of the strength properties of materials was also still hazy: although the idea of dislocations had been postulated by Orowan, Polanyi, and Taylor in 1934 and Griffith's foundations of fracture mechanics had been laid in 1920, our modern concepts of plastic deformation and fracture, and their interrelationship with material microstructure, were not developed until the 1950s and later.

Although it was generally agreed that the indentation test, and particularly the Brinell test, was extremely useful for practical purposes in industry, there was no consensus on what property of the material was actually being measured by indentation. For example, empirical correlations were noted (for pure metals) between indentation hardness and bulk modulus, absolute melting point, and thermal expansion coefficient; and although correlations with some mechanical strength properties such as proof stress, ultimate tensile stress, and fatigue limit were also known, the possibility of a theoretical basis for some of these correlations was not appreciated. O'Neill commented in 1934 that 'in the realms of hardness, practice has outstripped theory'.[12] An empirical correlation between Brinell hardness H_B and ultimate tensile stress σ_u for metals, and especially for steels, was widely appreciated. Brinell himself had found[7] that for steels with a wide range of carbon contents, there was a linear relationship:

$$\sigma_u = cH_B \quad , \tag{4}$$

with $c = 0.346$. By the 1940s, such a linear relationship was well established. Values for c of 0.36 and 0.34 were quoted in a German DIN standard for different types of steels.[14] Lea[13] in 1936 provided experimental measurements of Vickers hardness and various mechanical properties for a range of carbon and low alloy steels after different heat treatments and concluded that 'it does not appear possible to find for steels any property other than the ultimate tensile strength (or the maximum shear stress during a tensile test which is equal to one half of the tensile stress) which has approximately a constant ratio to the hardness number'. O'Neill stated in 1934[12] that although there did not seem to be a constant value of c for all metals, if they showed little work hardening then $c = 0.36$. However, he concluded that 'the theoretical reason for a constant relation between ultimate tensile stress and hardness is somewhat obscure'.

Despite the lack of understanding of the microstructural basis for work hardening, or indeed for any hardening processes in metals, there was a good appreciation dating back to the work of Brinell that the process of forming a ball indentation in a metal resulted in some local work hardening of the material. The work of Meyer was widely cited and influential,[8] and O'Neill subsequently referred to it as representing 'some of the most important work carried out on the subject of hardness'.[12] Meyer deduced from ball indentation experiments on a wide range of metals that the chordal diameter d of the indentation after unloading was related to the applied load according to:

$$W = kd^{\mathrm{n}} \quad , \tag{5}$$

where k is a constant of proportionality. The exponent n, generally known as the Meyer index, was found to depend on the state of work hardening of the metal and to be effectively independent of the size of the indenting ball; for a material with no capacity for strain hardening (i.e., fully work hardened), $n = 2$. For metals that are work hardened by the indentation process, $n > 2$.

Meyer also showed that the value of k decreased with increasing ball diameter such that for different ball diameters D_{i}

$$A = k_1 D_1^{n-2} = k_2 D_2^{n-2} = k_3 D_3^{n-2} \quad . \tag{6}$$

This behavior means that, in general, for $n > 2$, the mean pressure acting during a hardness indentation as defined by Eq. (2) will vary with the ball diameter or load, unless the ratio W/D^2 is maintained constant, which will lead to indentations that are geometrically similar, i.e., with the same ratio d/D. Meyer had shown that the same hardness would be derived from indentations with balls of different diameters only if the indentations were geometrically similar, and this was well appreciated, as was the fact that pyramidal or conical indenters produce indentations that are always geometrically similar. The relationships described by Eqs. (5) and (6) are commonly known as Meyer's laws.

O'Neill[12] commented that the Brinell hardness 'cannot be expressed (except when $n = 2$) by a single number, for it varies with the degree of deformation. A single hardness value can only properly be reported when qualified by a statement of the specific degree of deformation involved in securing that value, and it only represents, of course, a single point on the hardness-strain curve. In tensile testing the whole stress-strain diagram is much more valuable than any one point on that diagram.... The Brinell number provides a single point on the full hardness curve and ... has only limited significance'. Despite the insight suggested by this and other statements, the possibility of a deeper link between indentation hardness and the tensile stress-strain curve was not spelled out clearly until 10 years later. As early as 1908, Kürth, for example, had performed ball indentation tests on samples of copper and other metals that had previously been work hardened by controlled amounts of plastic tensile strain; his results were carefully reanalyzed by O'Neill[12] and Späth,[14] and O'Neill himself performed similar experiments, but the parallel between the tensile stress-strain curve and the increasing strain introduced by ball indentations with increasing loads was not drawn by these or other researchers until O'Neill's important paper of 1944.[18]

Thus, indentation hardness testing in the first half of the 20th century was widely used, recognized by national standards bodies, and capable of generating reproducible and accurate results of great practical value. However, despite the availability of extensive empirical data and the emergence of some sound but poorly understood rules and correlations, the scientific foundations of the indentation test and its interpretation were not at all widely appreciated.

III. 'THE HARDNESS OF METALS' (1951) AND SUBSEQUENT RESEARCH

Tabor's interest in hardness originated during his earliest research into the true area of contact between solids,[3] in which he modeled the plastic deformation of asperities by the assumption of a constant pressure acting at the contact. This model was supported by experimental measurements on crossed cylinders of steel and silver, loaded against each other: a mutual indentation geometry in which the contact zone is similar to that of a sphere on a plane. In this work, he made use of the well established concept of a constant plastic indentation pressure, and its great novelty and value lay in understanding the factors that control the true contact area rather than in any analysis of hardness.

Tabor's first publication that explicitly addressed hardness[19] was based on work performed in Australia and Cambridge, and represented a landmark in the development of the subject: discussed the shallowing of spherical indentations on the removal of load, the measurement of dynamic hardness, and what he called 'a simple theory of hardness', which instantly placed the science of indentation testing on a straightforward theoretical basis that could be readily understood.

The fact that, once the load has been removed, the indentation made by a spherical indenter has a larger radius of curvature than the indenter itself was well known,[12] and careful measurements of the effect had been reported. What was lacking was a theoretical treatment of the effect. Tabor showed, using his own measurements and those of others, that the Hertz model for the elastic contact deformation of spherical bodies could predict the effect accurately. He also clearly described in qualitative terms how indentation by a ball initially led to elastic deformation, then to plastic flow and associated work hardening, and then on removal of the load to elastic recovery. The initial and final elastic stages could, it seemed, be modeled well by the Hertz equations. The work on rebound hardness followed naturally from this picture, because the kinetic energy of a rebounding ball originates from the elastic recovery process, and Tabor showed how this leads to an analytical model for the rebound of a ball that agreed well with experimental data for a wide range of metals.

Elastic shallowing and rebound hardness measurements are of quite minor practical importance, and in retrospect the third part of the paper was the most significant. Here, Tabor applied recent developments in continuum mechanics to the plastic stage of indentation. The early part of the century had seen major advances in the theoretical treatment of plastic flow (as summarized by Timoshenko[20]), and models for plastic indentation were further developed in the context of projectile penetration, notably by Hill and colleagues.[21–23] Tabor noted that these studies of plane-strain indentation in a rigid-plastic material, and also recent work by Ishlinsky[24] for a spherical indenter that he had himself translated from the original Russian, all predicted a value of approximately 3 for the constraint factor, the ratio C between the mean contact pressure P_{m} and the uniaxial yield stress Y:

$$P_{\mathrm{m}} = CY \quad . \tag{7}$$

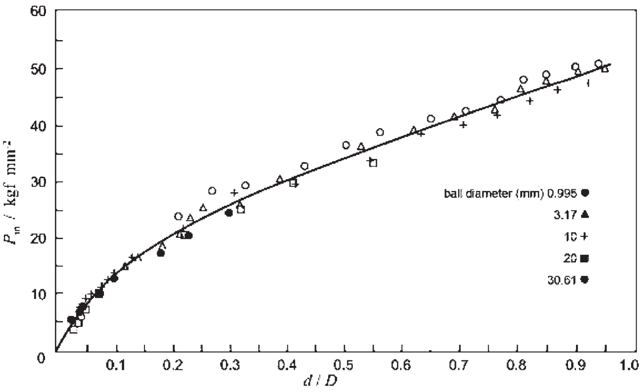

FIG. 3. Variation of mean indentation pressure P_{m} with the ratio d/D for indentation of annealed copper by spheres of various diameters (after Tabor,[19] based on data from Krupkowski).

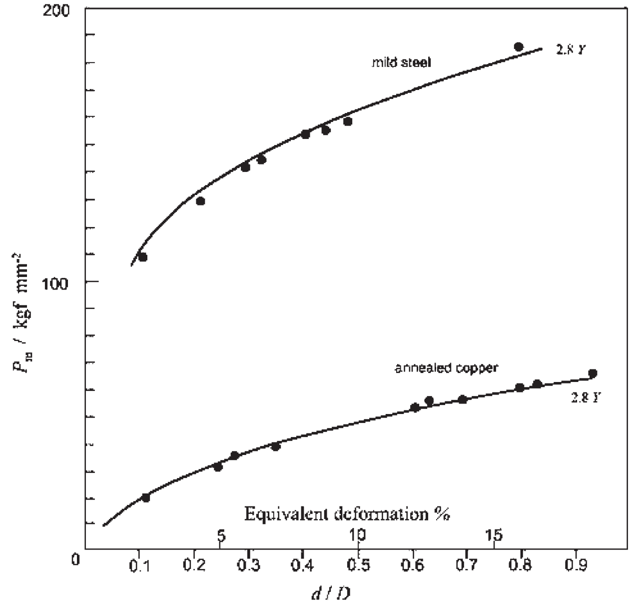

FIG. 4. Data points showing the variation of mean indentation pressure P_{m} with the ratio d/D for ball indentation of mild steel and annealed copper, compared with solid curves derived from stress-strain curves measured in uniaxial compression (after Tabor[19]).

For a material that showed no work hardening, a theoretical basis that supported the purely empirical Eq. (4) was thus immediately apparent. Tabor suggested that geometrically similar indentations would induce similar strain distributions and that a 'representative strain' proportional to d/D might be used to characterize the strain field; he then demonstrated from experimental data published earlier by Krupkowski that geometrically similar indentations in a work-hardening metal showed identical values of P_{m}, as expected (Fig. 3). The next step was to show that for work-hardening metals, a plot of the mean indentation pressure versus d/D closely reproduced the compressive (or tensile) true stress strain curve if the pressure and uniaxial stress were related by Eq. (7) with $c = 2.8$, and the 'representative strain' was taken to be 0.2 d/D (Fig. 4). In addition, Tabor demonstrated that for a metal that exhibited power-law strain-hardening, where the instantaneous true flow stress Y was related to the true strain ε by $Y = b\varepsilon^{x}$, Meyer's laws could be derived from the assumption that the strain was proportional to d/D and that the Meyer index n would then be equal to $(2 + x)$. Finally, Tabor showed experimentally that a 'representative strain' of approximately 8% was associated with the geometrically similar indentations formed by the pyramidal Vickers indenter. Thus, Tabor built up a theoretical model for the indentation of metals, validated by his experiments and the experiments of others, which in principle could explain the correlation between hardness and tensile strength, the variation of hardness seen in strain-hardening materials and expressed empirically by Meyer's laws, and the differences between the hardness values measured with indenters of different geometries. It provided a direct and quantitative link between the hardness test and the tensile or compressive stress-strain curve. The basic concepts demonstrated in this first paper have provided the foundations for the understanding of indentation hardness developed by Tabor and other investigators in subsequent work.

The elements from which Tabor constructed his model for indentation hardness were clearly in existence before 1948. As indicated above, Eq. (7) emerged from analyses of indentation in a rigid-plastic half-space performed during World War II. The power-law relationship had been used to describe the stress-strain behavior of work-hardening materials since early in the century, and was discussed by Nadai[25] in his 1931 textbook on plasticity. The observation that geometrically similar indentations lead to the same value of hardness dates back to the work of Meyer. The use of the ratio d/D or its logarithm to describe the strain introduced by ball indentation had been suggested by O'Neill in 1944,[18] who had also plotted the P_m against $\log(d/D)$ (as shown in Fig. 5) and noted the similarity of such a plot to the corresponding tensile true stress-true strain curve. O'Neill had also suggested a relationship between the Meyer index n and the strain-hardening exponent x, and Tabor was evidently familiar with O'Neill's work, which he cited in his 1948 paper. The originality of Tabor's approach lay in merging these various contributions together, in 'boldly assuming' (as Chaudhri has commented[26]) that Eq. (7) could be applied to the indentation of a strain-hardening metal, and in forging a quantitative link, through this equation and the assumption of a 'representative strain' proportional to d/D, between the results of ball indentation and the tensile or compressive stress-strain curve. The assumptions underlying this model have subsequently been broadly supported by theoretical treatments of indentation by both spherical[27,28] and conical indenters.[29]

Tabor's short book 'The Hardness of Metals',[30] published in 1951 and republished in 2000, added valuable flesh to the bones of his 1948 paper, and it is rightly regarded as a classic text. It made a remarkable impact on the development of the science of indentation hardness, as illustrated in Table I, which shows the number of papers abstracted by a major scientific database and published between 1970 and 2007, that cited various books on the topic of hardness. The number of citations given to Tabor's book (1592 over this period) was more than three times the number received by all of the other books taken together and more than six times the number received by the next most highly cited (by Mott[32]). In the more discursive format appropriate to a book, Tabor expanded on the ideas presented in his 1948 paper, providing more background material on plasticity and strength of materials as well as new experimental evidence to strengthen the picture of indentation developed in the paper. The additional material in the book provided extra theoretical support for important concepts in ball indentation: the initiation of plastic flow at a pressure of approximately 1.1Y (benefiting from the recent work of Davies[35]); the transition to full plasticity; and deformation of the indenter (supporting empirical conventions about the minimal hardness required in the ball). A more substantial treatment of Vickers indentation and new material on the Rockwell test further contributed to a text which was more directly useful to the practical scientist or materials testing engineer than the earlier paper, and appendixes of typical hardness values, conversions, and other data added to this value.

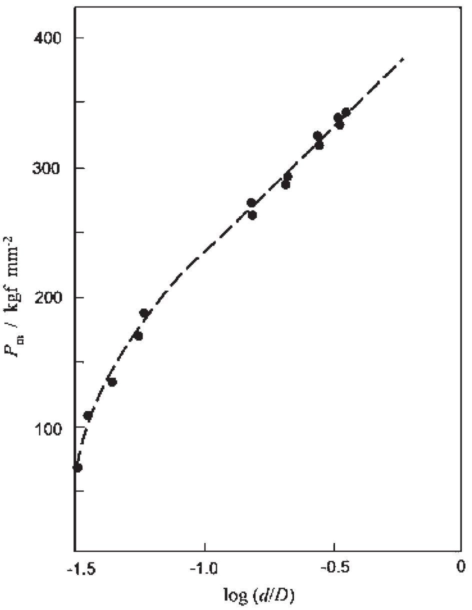

FIG. 5. Variation of P_m with $\log(d/D)$ for ball indentation of a medium carbon steel; the broken line is a fit to the data points (after O'Neill[18]).

TABLE I. Books published between 1934 and 1973 on the topic of hardness, showing the numbers of papers published between 1970 and 2007 (inclusive) that have cited them (data are obtained from Science Citations Index Expanded).

Year published	Book author/reference	Number of times cited 1970–2007
1934	O'Neill[12]	32
1936	Lea[13]	2
1940	Späth[14]	1
1942	Williams[15]	17
1949	Lysaght[16]	18
1951	Tabor[30]	1592
1952	von Weingraber[31]	4
1956	Mott[32]	257
1967	O'Neill[33]	101
1973	Westbrook and Conrad[34]	89

The ability to predict properties from indentation experiments which until then had only been accessible by tensile testing, once the underlying theory had been developed, was apparent to Tabor. He showed how the ultimate tensile strength could be derived by indentation even for work-hardening metals, as long as power-law hardening could be assumed. He demonstrated this in his book, and further developed the concept in a paper[36] which extended his earlier treatment to include pyramidal and conical indenters.

Up to this point, all of Tabor's studies had been on metals, but he rapidly took an interest in the indentation response of polymers and of macroscopically brittle materials in the context of studies of the friction of these materials. It should be recalled that the polymer industry was still in its infancy, and that widespread development and use of polymers and engineering ceramics was yet to come. King and Tabor[37] reported Vickers hardness measurements on polyethylene, PMMA, PTFE, and a further halocarbon polymer, using the data to estimate the yield pressure. In subsequent work, Pascoe and Tabor[38] carried out ball indentation tests as well as mutual indentation of crossed cylinders (the method used by Bowden and Tabor in 1939) and showed that a range of polymers obeyed Meyer's laws. King and Tabor[39] made Vickers indentations in single-crystal rock salt, and noted that the response was plastic, ascribing the absence of fracture to the high hydrostatic stress beneath the indenter; they found that the values of yield stress derived from the indentation pressure matched those from direct compression experiments well, with the same constant of proportionality C as for metals. The latter study, together with Tabor's earlier work on indentation hardness and a more recent study of the Mohs scratch hardness test,[40] was summarized in a 1956 conference paper.[41]

The 1960s saw renewed work in Tabor's group on the indentation of metals with two main themes: (i) more detailed study of geometrically similar indentations as well as of mutual indentation and (ii) tests at high temperatures, including indentation creep. Stilwell and Tabor[42] extended Tabor's earlier work on the elastic recovery and shallowing of spherical indentations to examine the indentations formed by cones. They showed that, once again, the main effect of unloading was a reduction in indentation depth, and they found excellent agreement with a theoretical treatment based on the Boussinesq elastic solution. Atkins and Tabor[43–45] studied in detail the indentation of metals by cones and pyramids with different included angles, and mutual indentation of crossed cylinders and wedges. By building on Tabor's earlier concepts, and by carrying out indentation experiments on metals with various degrees of work hardening, they showed how the representative strain associated with a cone or pyramid depended on its geometry, and how it was possible to construct the stress-strain curve by using a series of indenters with differing geometries. They demonstrated that Meyer's laws were obeyed for crossed cylinders in mutual indentation experiments, and that the behavior of wedges paralleled that of geometrically similar indenters. They also showed how the constant of proportionality C between the indentation pressure P_m and the yield stress Y depended on the indenter shape, and they found that this variation reflected changes in the plastic strain field beneath the indenter.

Mulhearn and Tabor[46] used indentation to study the creep of lead and indium, with a much more substantial study of these metals as well as of aluminium, magnesium oxide, and tungsten carbide being subsequently performed by Atkins, Silverio, and Tabor.[47] Indentation is associated with a complex elastic-plastic stress field that expands as the indentation grows; it is much more difficult to model the process of indentation creep than, for example, creep in uniaxial tension. However, by assuming that the growth of the indentation resembles the expansion of a hemispherical cavity in a semi-infinite plastic solid, a suggestion made to the authors by Hill, Atkins, et al.[47] found good agreement between their experiments and a model based on a transient creep equation of state. Indentation provides a valuable method to measure the plastic properties of materials at high temperatures, and Atkins and Tabor[48,49] applied mutual indentation to good effect in studying the short-term plastic flow, as well as the creep deformation, of a range of ceramic materials at temperatures up to 2000 °C.

In 1970, Tabor surveyed the science of indentation hardness in a characteristically lucid and balanced review. This comprehensive paper,[50] which provided an excellent update to his book, summarized the work of his own group over the previous 20 years, but it also noted the significant advances that had been made by others. Topics that Tabor himself had not studied but which he addressed here included the variation of hardness with grain size in metals, the anisotropy observed in tests on single crystals, and advances in the theoretical treatment of the indentation process, especially for materials which show significant elastic strains. The extension of the hemispherical cavity model for indentation of an elastic-plastic material by Johnson,[51] who showed how the influence of indenter shape could be incorporated, was judged by Tabor to lead to 'probably the most useful indentation curve that has, as yet, been derived'.

Also discussed in the 1970 review was the recent work performed in PCS by Gane,[52] who initially working with Bowden[53] had performed innovative experiments involving indentation at low loads (from 10 mN to 10 μN) on gold samples inside an SEM, at a very early stage in the development of such instruments. In this pioneering study, Gane showed how the strength properties of a material at small scales could be measured by indentation, and that they might well differ from those measured at larger scales. This work led to further studies of adhesion, elastic, and plastic effects associated with contact and indentation at small loads and length scales.[54–57] Although Tabor initially encouraged the use of the term ‘picohardness’ in this context,[58] this important and now active area of research and measurement has subsequently become known as ‘nanoindentation’ and ‘nanohardness’.

Tabor’s reputation and expertise attracted researchers who studied indentation to his laboratory throughout the 1970s, generating what might today be called a ‘center of excellence’. Whereas some of those researchers made significant studies of the phenomena of indentation fracture,[59,60] Tabor himself published only one paper on this topic,[61] and his own personal interest in indentation remained focused on more ductile materials. Tabor and Gerk[62,63] explored the ductile indentation of semiconductors such as silicon and germanium, and the then novel suggestion that these and other materials with the diamond structure might transform to a metallic, conducting phase under the high hydrostatic stress beneath the indenter; Tabor summarized this work and discussed other recent developments in indentation, in a contribution to a Festschrift for Walter Boas, whom he had first met in Australia more than 35 years earlier.[64]

After retiring from his university professorship in 1981, Tabor published three additional review papers on indentation hardness in which he continued to demonstrate a keen interest in developments in indentation science, both experimental and theoretical.[58,65,66] The first of these papers includes practical comments and advice on measurement of hardness aimed at the practical scientist and engineer, an audience from which Tabor was never far away. He profited considerably from interactions with theoreticians, notably Rodney Hill in his earlier work, and later Kenneth Johnson, both of whom were colleagues in Cambridge. However, regardless of the mathematical complexity, Tabor always looked for a simple physical model. The record of the discussion after one of Tabor’s early expositions on hardness to an audience of practical engineers[67] summarizes his views: ‘Dr Tabor preferred the simple picture which could be readily grasped and applied, even though the fit might not be perfect. He thought this was better than looking for something which would give a better fit but which was so complicated that it could only with very great difficulty be comprehended and applied.’ Later, in a lecture entitled ‘The Contribution of the Physicist to Tribology’,[68] Tabor wrote that ‘above all (the physicist) needs physical insight and a sense of reality. Without these attributes he will amass expensive equipment and meaningless data.’ Thirty years later, in one of his final papers,[65] Tabor continued to express skepticism about the possibility of exact theoretical models for indentation: ‘My impression remains that hardness measurements which involve very complex elastic and plastic stresses and strains, as well as possible surface interactions, are bound to be complex. It is not clear that theoretical analyses can yet fully cover all aspects of the process. Maybe because indentation experiments are so simple and convenient we are misled into believing that their unsophisticated interpretation will provide precise information concerning the elastic and plastic properties of the specimen.’

IV. CONCLUSIONS

David Tabor’s contribution to the science of indentation hardness, his interest in which started with his first published paper in 1939 and continued until his last paper almost 60 years later, was immense. The scientific basis for the indentation test had been only poorly appreciated when Tabor published his ground-breaking ‘simple theory’ in 1948: a model based on recent theoretical developments, careful experiments, and not a little inspiration, which provided the physical insight to drive the subject forward, and formed the basis of his own work and that of his collaborators, for the next 30 years. His book on hardness remains the most highly cited text on the subject by a large margin, more than 50 years after publication. All those working in the field of indentation science owe him a great debt.

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REFERENCES

1. I.M. Hutchings and B.J. Briscoe: Obituary—David Tabor 1913–2005. *Wear* **260,** 1151 (2006).
2. J.E. Field: David Tabor. *Biog. Memoirs Fellows of the Royal Society* **54,** 425 (2008).
3. F.P. Bowden and D. Tabor: The area of contact between stationary and between moving surfaces. *Proc. R. Soc. London, Sect. A* **169,** 391 (1939).
4. N.N. Greenwood and J.A. Spink: An antipodean laboratory of remarkable distinction. *Notes Rec. R. Soc. Lond.* **57,** 85 (2003).
5. F.C. Calvert and R. Johnson: On the hardness of metals and alloys. *Philos. Mag. 4th series* **17,** 114 (1859).
6. J.A. Brinell: Way of determining the hardness of bodies and some applications of the same. *Teknisk Tidskrift.* **5,** 69 (1900).
7. A. Wahlberg: Brinell’s method of determining hardness and other properties of iron and steel. *J. Iron. Steel Inst.* **59,** 243 (1901).
8. E. Meyer: Investigations of hardness testing and hardness. *Phys. Z.* **9,** 66 (1908).
9. R. Smith and G. Sandland: An accurate method of determining the hardness of metals, with particular reference to those of a high degree of hardness. *Proc. Instn. Mech. Engrs.* **1,** 623 (1922).
10. S.P. Rockwell: The testing of metals for hardness. *Transactions of the American Society for Steel Treating* **2,** 1013 (1922).
11. H.M. Rockwell and S.P. Rockwell: Hardness-tester. U.S. Patent No. 1294171 (1914).
12. H. O’Neill: *The Hardness of Metals and Its Measurement* (Chapman and Hall, Ltd., London, England, 1934).
13. F.C. Lea: *Hardness of Metals* (C. Griffin, London, England, 1936).

14. W. Späth: *Physics and Technology of Hardness and Softness.* (Springer, Berlin, 1940).
15. S.R. Williams: *Hardness and Hardness Measurements* (The American Society of Metals, Cleveland, OH, 1942).
16. V.E. Lysaght: *Indentation Hardness Testing* (Reinhold Publishing Corporation, NY, 1949).
17. L.B. Tuckerman: Hardness and hardness testing. *Mech. Eng.* **47,** 53 (1925).
18. H. O'Neill: The significance of tensile and other mechanical test properties of metals. *Proc. Inst. Mech. Engrs.* **151,** 116 (1944).
19. D. Tabor: A simple theory of static and dynamic hardness. *Proc. R. Soc. London, Ser. A* **192,** 247 (1948).
20. S.P. Timoshenko: *History of Strength of Materials* (McGraw-Hill, NY, 1953).
21. R.F. Bishop, R. Hill, and N.F. Mott: The theory of indentation and hardness tests. *Proc. Phys. Soc. London* **57,** 147 (1945).
22. R. Hill, E.H. Lee, and S.J. Tupper: The theory of wedge indentation of ductile materials. *Proc. R. Soc. London, Ser. A* **188,** 273 (1947).
23. R. Hill: *The Mathematical Theory of Plasticity* (Clarendon Press, Oxford, UK, 1950).
24. A.J. Ishlinsky: The axial-symmetrical problem in plasticity and the Brinell hardness. *J. Appl. Math. Mech. (USSR)* **8,** 233 (1944).
25. A. Nadai: *Plasticity* (McGraw-Hill, NY, 1931).
26. M.M. Chaudhri: Subsurface plastic strain distribution around spherical indentations in metals. *Philos. Mag. A* **74,** 1213 (1996).
27. R. Hill, B. Storakers, and A.B. Zdunek: A theoretical study of the Brinell hardness test. *Proc. R. Soc. London, Ser. A* **423,** 301 (1989).
28. S. Biwa and B. Storakers: An analysis of fully plastic Brinell indentation. *J. Mech. Phys. Solids* **43,** 1303 (1995).
29. Y-T. Cheng and Z. Li: Hardness obtained from conical indentations with various cone angles. *J. Mater. Res.* **15,** 2830 (2000).
30. D. Tabor: *The Hardness of Metals* (Clarendon Press, Oxford, UK, 1951).
31. H. von Weingraber: *Technical Hardness Measurement* (Carl Hanser Verlag, Munich, 1952).
32. B.W. Mott: *Micro-indentation Hardness Testing* (Butterworths, London, UK, 1956).
33. H. O'Neill: *Hardness Measurement of Metals and Alloys* (Chapman and Hall, London, UK, 1967).
34. J.H. Westbrook and H. Conrad: *The Science of Hardness Testing and Its Research Applications* (American Society for Metals, Metals Park, OH, 1973).
35. R.M. Davies: The determination of static and dynamic yield stresses using a steel ball. *Proc. R. Soc. London, Ser. A* **197,** 416 (1949).
36. D. Tabor: The hardness and strength of metals. *J. Inst. Metals* **79,** 1 (1951).
37. R.F. King and D. Tabor: The effect of temperature on the mechanical properties and the friction of plastics. *Proc. Phys. Soc. London, Sect. B* **66,** 728 (1953).
38. M.W. Pascoe and D. Tabor: The friction and deformation of polymers. *Proc. R. Soc. London, Ser. A* **235,** 210 (1956).
39. R.F. King and D. Tabor: The strength properties and frictional behaviour of brittle solids. *Proc. R. Soc. London, Ser. A* **223,** 225 (1954).
40. D. Tabor: Mohs's hardness scale—A physical interpretation. *Proc. Phys. Soc. London Sect.* **67,** 249 (1954).
41. D. Tabor: The physical meaning of indentation and scratch hardness. *Br. J. Appl. Phys.* **7,** 159 (1956).
42. N.A. Stilwell and D. Tabor: Elastic recovery of conical indentations. *Proc. Phys. Soc. London* **78,** 169 (1961).
43. A.G. Atkins and D. Tabor: Plastic indentation in metals with cones. *J. Mech. Phys. Solids* **13,** 149 (1965).
44. A.G. Atkins and D. Tabor: On 'indenting with pyramids'. *Int. J. Mech. Sci.* **7,** 647 (1965).
45. A.G. Atkins and D. Tabor: Mutual indentation hardness apparatus for use at very high temperatures. *Br. J. Appl. Phys.* **16,** 1015 (1965).
46. T.O. Mulhearn and D. Tabor: Creep and hardness of metals: A physical study. *J. Inst. Metals* **89,** 7 (1960).
47. A.G. Atkins, A. Silvério, and D. Tabor: Indentation hardness and the creep of solids. *J. Inst. Metals* **94,** 369 (1966).
48. A.G. Atkins and D. Tabor: The plastic deformation of crossed cylinders and wedges. *J. Inst. Metals* **94,** 107 (1966).
49. A.G. Atkins and D. Tabor: Mutual indentation hardness of single-crystal magnesium oxide at high temperatures. *J. Am. Ceram. Soc.* **50,** 195 (1967).
50. D. Tabor: The hardness of solids. *Rev. Phys. Technol.* **1,** 145 (1970).
51. K.L. Johnson: The correlation of indentation experiments. *J. Mech. Phys. Solids* **18,** 115 (1970).
52. N. Gane: The direct measurement of the strength of metals on a sub-micrometre scale. *Proc. R. Soc. London, Ser. A* **317,** 367 (1970).
53. N. Gane and F.P. Bowden: Microdeformation of solids. *J. Appl. Phys.* **39,** 1432 (1968).
54. J.B. Pethica and D. Tabor: Contact of characterised metal surfaces at very low loads: Deformation and adhesion. *Surf. Sci.* **89,** 182 (1979).
55. M.D. Pashley and D. Tabor: Adhesion and deformation properties of clean and characterized metal microcontacts. *Vacuum* **31,** 619 (1981).
56. J.B. Pethica and D. Tabor: Characterized metal microcontacts. *J. Adhes.* **13,** 215 (1982).
57. M.D. Pashley, J.B. Pethica, and D. Tabor: Adhesion and micromechanical properties of metal surfaces. *Wear* **100,** 7 (1984).
58. D. Tabor: Indentation hardness and its measurement: Some cautionary comments, in *Microindentation Techniques in Materials Science and Engineering (ASTM STP 889)*, edited by P.J. Blau and B.R. Lawn (American Society for Testing and Materials, Philadelphia, PA, 1986), pp. 129–159.
59. M.V. Swain and J.T. Hagan: Indentation plasticity and the ensuing fracture of glass. *J. Phys. D: Appl. Phys.* **9,** 2201 (1976).
60. C.G. Knight, M.V. Swain, and M.M. Chaudhri: Impact of small steel spheres on glass surfaces. *J. Mater. Sci.* **12,** 1573 (1977).
61. B.D. Powell and D. Tabor: The fracture of titanium carbide under static and sliding contact. *J. Phys. D: Appl. Phys.* **3,** 783 (1970).
62. A.P. Gerk and D. Tabor: Indentation hardness and semiconductor-metal transition of germanium and silicon. *Nature* **271,** 732 (1978).
63. D. Tabor: Phase changes and indentation hardness of germanium and diamond. *Nature* **273,** 406 (1978).
64. D. Tabor: Indentation hardness and yield properties of solids, in *Physics of Materials: Festschrift for Walter Boas*, edited by D.W. Borland (Melbourne, Australia, CSIRO, 1979), pp. 271–282.
65. D. Tabor: Indentation hardness and materials properties, in *Solid-Solid Interactions*, edited by M.J. Adams, S.K. Biswas, and B.J. Briscoe (Imperial College Press, London, UK, 1996), pp. 6–15.
66. D. Tabor: Indentation hardness: Fifty years on—A personal view. *Philos. Mag. A* **74,** 1207 (1996).
67. D. Tabor: The physical meaning of indentation hardness. *Sheet Metal Indust.* **31,** 749 (1954).
68. D. Tabor: The contribution of the physicist to tribology. *Proc. Inst. Mech. Eng.* **181,** 236 (1966).