

Results of a survey of the priorities for an increased range of UK traceable hardness scales

Francis Davis

August 2001

August 2001

Results of a survey of the priorities for an increased range of UK traceable hardness scales

Francis Davis

**Centre for Mechanical and Acoustical Metrology
National Physical Laboratory
Queens Road
Teddington
Middlesex
TW11 0LW**

Abstract

As part of the 1996-1999 NMS mass metrology programme, a project was launched to re-establish hardness standards for the highest priority scales. A consultative document published, in support of this re-establishment, stated that the scales supported were considered a minimum requirement, and that the future mass metrology programmes should reflect the need for an increased range of national traceable hardness scales.

This report has been written as part of deliverable 2.3.3 of the NMS mass metrology programme 1999 – 2002, “to establish the priorities for an increased range of hardness scales”. These priorities were derived from the analysis of a survey of both manufacturers and users of hardness equipment. The survey was carried out during June - August 2001 and circulated to the UK hardness community by use of the distribution lists of the BSI hardness committee (ISE/NFE/4/5), BMTA members, UKAS-accredited hardness laboratories, the NPL MATC Materials Measurement flyer, and the NPL Force and Hardness Group. The survey covers traditional indentation hardness methods, rubber hardness, and the instrumented indentation method for hardness and material properties. Provided as appendices to this report are background notes on hardness scales, the questionnaire that was circulated, and a list of the organisations that responded.

The report confirms that the highest priority scales that were established prior to the 1996 - 1999 NMS mass metrology programme were correct and provides a prioritised list of the hardness scales that require support from NPL’s hardness standards. The report also recommends the need for further work to be carried out to compare the hardness scales of hardmetal and hardened steel indenters to establish the scale difference. This comparison should include Rockwell and Superficial Rockwell hardness scales and also Brinell. It is considered that for the Brinell scales the comparison is less important as hardened steel indenters have been superseded, and only hardmetal indenters are specified in the BS/ISO standards. However, in niche industries the use of hardmetal indenters for Brinell is problematic and companies have expressed the need to continue measurement using hardened steel balls. As anticipated, Shore and IRHD hardness testing is used primarily by those organisations serving the polymer industry, whilst instrumented indentation techniques are of primary interest to the “thin” surface coatings industry.

© Crown Copyright 2001
Reproduced by permission of the Controller of HMSO

ISSN 1369-6785

National Physical Laboratory
Teddington, Middlesex TW11 0LW

Extracts from this report may be reproduced provided the source is acknowledged and the extract is not taken out of context.

Approved on behalf of the Managing Director, NPL,
by G R Torr, Head, Centre for Mechanical and Acoustical Metrology

Contents

1	Introduction	5
2	The Hardness Survey	6
2.1	Dissemination and Organisations Surveyed	6
2.2	Overview of the Questionnaire	6
3	Indentation Hardness	7
3.1	Brinell Hardness Scale	7
3.2	Rockwell and Superficial Rockwell Scales	8
3.3	Vickers Hardness Scale	10
3.4	Summary of Indentation Hardness	11
4	Elastomer/Polymer Hardness Scales	12
5	Instrumented Indentation Hardness Scales	12
6	Conclusions and Further Work	12
7	Acknowledgments	13
8	References	14
	Appendix 1: Background Notes on Hardness Scales	15
	Appendix 2: The Hardness Questionnaire	24
	Appendix 3: Organisations that Responded to the NPL Hardness Survey	30

1 Introduction

As part of the 1996 – 1999 DTI’s National Measurement System (NMS) Programme for Mass it was agreed that the UK national standards for hardness should be re-established to cover the highest priority Brinell, Rockwell, and Vickers hardness scales. An NPL report [1] submitted on completion of the contract MPU 8/45.4 “Provision of hardness standards” provides detail of the purchase and commissioning of hardness machines and the ancillary equipment required to re-establish a UK hardness calibration service. It also reviews the main factors contributing to the uncertainty of hardness measurement and highlighted the need for improvements in the Rockwell hardness machine, in particularly the depth sensing technique.

A consultative survey [2] of UK industry was carried out, as part of the re-establishment of the UK hardness standards, to identify the highest priority indentation hardness scales. The scales, shown in Table 1, were also based on those requested by the British Measurement and Testing Association (BMTA) and agreed with the United Kingdom Accreditation Service (UKAS).

Table 1. Hardness scales supported.

	Scales	Nominal Force (N)
Brinell	HB10/3000	30 000
	HB10/1000	10 000
	HB5/750	7 500
	HB2.5/187.5	1 900
Rockwell	HRB	100 to 900
	HRC	100 to 1 500
Superficial Rockwell	HR30N, HR30T	100 and 300
Vickers	HV10	100
	HV30	300

These hardness scales (Table 1) were seen as the minimum requirement and the priorities for an increased range of national traceable hardness standards would be surveyed as part of the 1999 – 2002 NMS mass metrology programme.

A hardness survey to establish the priorities for an increased range of hardness scales was carried out during June - August 2001. The survey was primarily aimed at the need to extend the traditional indentation hardness scales. However, the survey included limited questions on the need for NPL’s support of elastomeric/polymeric material hardness standard, such as Shore and IHRD test methods. The reason for their inclusion was due to the high number of enquiries made of the NPL hardness standards regarding Shore hardness and, in particular, the use of conversion scales with other hardness test methods. The survey also included a section on instrumented indentation hardness testing for which ISO standards [3] are in the process of being drafted. This technique provides the ability to measure the indenter penetration under the applied force throughout the test cycle and measures both the plastic and elastic deformation of the material under test. Although still under development it is considered that this hardness test may eventually replace the traditional indentation scales as the test provides additional information on material properties.

The survey questioned both manufacturers and industrial users of hardness equipment on the importance of individual hardness scales to their organisation, and covered the following hardness scales:

- Brinell hardness
- Rockwell and Superficial Rockwell hardness
- Vickers hardness
- Elastomers/Polymers hardness
- Instrumented indentation for hardness and material properties

This report summarises the response to the survey and confirms the hardness scales most commonly used in the UK hardness industry as those shown in Table 1. Further, the report provides a preliminary prioritised list of additional hardness scales that require support from UK NMS hardness standards. This prioritised list will be offered for discussion at an NPL Focus Group meeting concerned with the formulation of the next (2002 – 2005) NMS mass metrology programme.

Provided as Appendix 1 and 2 to this report are the background notes on hardness scales and the questionnaire that was circulated as the hardness survey.

2 The Hardness Survey

2.1 Dissemination and Organisations Surveyed

The survey was widely disseminated to interested parties by use of the distribution lists of the BSI hardness committee (ISE/NFE/4/5), BMTA members, UKAS accredited hardness laboratories, the NPL MATC Materials Measurement flyer, and the NPL Force and Hardness Group. The survey included manufacturers of hardness machines for metallic and elastomer/polymer materials, and suppliers of hardness test blocks and indenters from the UK. The users of hardness testing equipment were very diverse and included both material suppliers, end-users, commercial/research test-houses and consultants. The material suppliers covered organisations from many industrial sectors, including: ferrous and non-ferrous, glasses and ceramics, elastomers and polymers, and engineering coatings. Whilst the industrial end-users included: automotive and aerospace, clothing and textile, power and petrochemical, food processing and health care. Appendix 3 lists the 74 organisations that responded to the hardness survey.

2.2 Overview of the Questionnaire

The majority of the manufacturers surveyed, manufacture Brinell, Rockwell and Vickers machines, whilst a few also manufacture or supply Shore hardness testers, Scleroscope type hardness testers, instrumented indentation techniques and, other portable hardness machines. The users, depending upon their industry, are reliant mainly on Rockwell and Vickers hardness testing. Brinell hardness testing is used primarily for quality control of incoming raw metallic materials, and the choice of scale depends on whether the metal is ferrous or non-ferrous. Hardness test users also indicated an interest in micro-Vickers and Knoop testing, and both Shore and IRHD hardness testing for elastomeric/polymeric materials. Niche industrial users expressed interest in the development of instrumented indentation techniques for the assessment of thin surface coatings, including paint films, whilst manufacturers of traditional indentation hardness machines are keeping a watching brief.

Analyses of the replies to the questionnaire are presented in the following sections and are compiled by considering the importance of national traceability for the individual hardness scales. The simple rating system used in the survey was that “1” was considered as unimportant or not-relevant, and that “4” was considered as very important to the UK hardness industry. Therefore in the graphs shown, the higher the column the greater the relative importance of the hardness scale. The replies were considered as those from the manufacturers of hardness machines and ancillaries, i.e. test blocks and indenters, and those replies from the industrial users of hardness equipment. In addition, the overall relative importance of support for the hardness scale was considered and averaged. Some comparisons are made of the relative importance of the traditional indentation hardness. However, much care must be exercised in comparing the importance of such techniques with the hardness methods used for elastomers/polymers and the newly developed instrumented indentation technique.

3 Indentation Hardness

3.1 Brinell Hardness Scales

Figure 1 shows the rating of the individual Brinell hardness scales. The results show, not unexpectedly, that support to the Brinell range of scales was of greater importance to the manufacturers of hardness machines and ancillary hardness equipment rather than the industrial users. This figure also confirms that the conclusions of the earlier consultative study [2] into the most important Brinell hardness scales were correct.

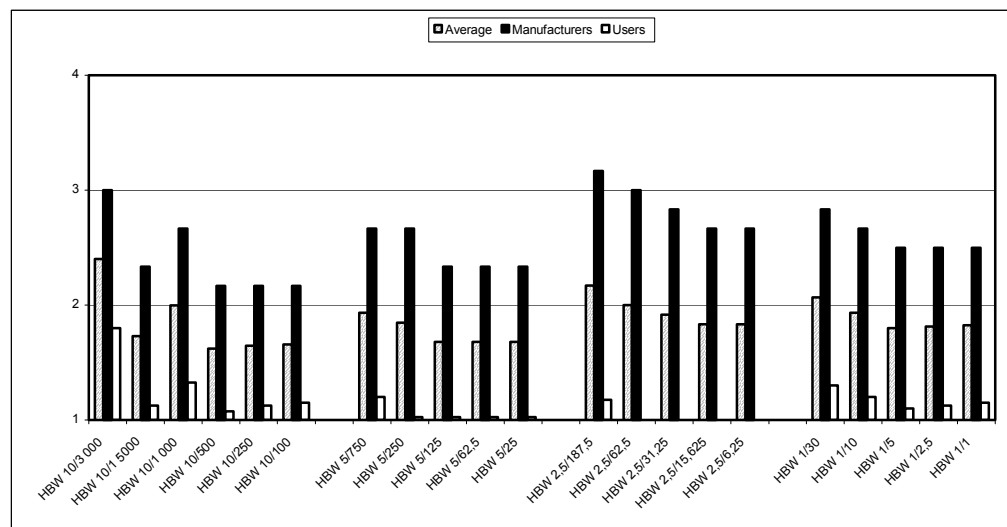


Figure 1. Analysis of the Brinell hardness scales.

Further analysis of the data (Figure 2) showed that for the manufacturers of Brinell hardness equipment the most important indenter was the 2.5 mm diameter ball, both the 5 mm and 10 mm diameter indenter had approximately the same rating with the 1 mm diameter indenter having a marginally greater rating.

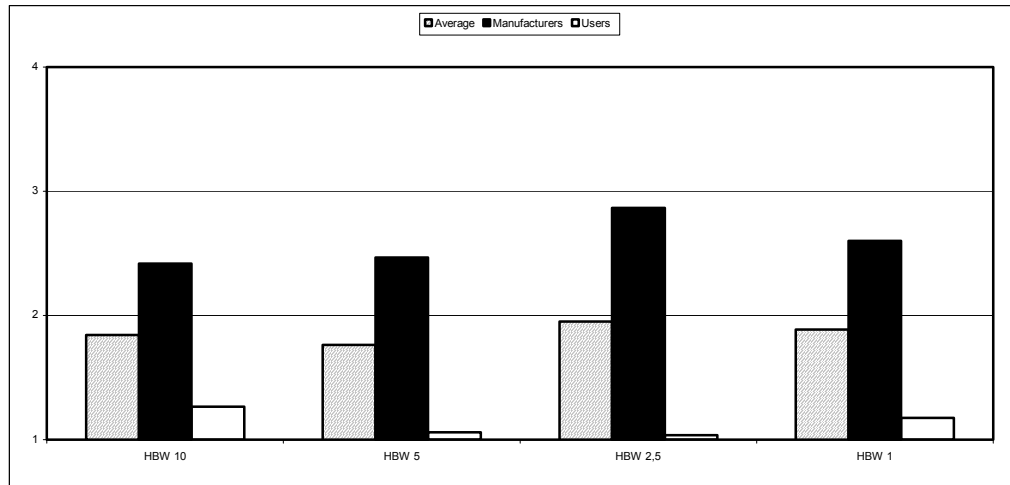


Figure 2. The relative importance of indenter diameter.

In comparison, the results of the users showed that the 10 mm diameter ball rated the highest, followed by the 1 mm 5 mm and 2,5 mm diameter ball indenters. This relatively greater interest in the 1 mm diameter balls agrees with the consultative study [2] which reported the requirement for Brinell calibrations at low force, and therefore small indenter diameter.

Regarding indenter metallurgy and despite the standard only specifying the use of tungsten carbide indenters, there was a majority interest in establishing the difference between hardmetal and hardened steel indenters. Of particular note, was the comment from the manufacturers of titanium and its alloys and that the use hardened steel ball indenters would continue, as tungsten carbide is considered a high-risk material and can lead to production problems.

3.2 Rockwell and Superficial Rockwell Hardness Scales

The result of the Rockwell and Superficial Rockwell hardness survey is shown in Figure 3.

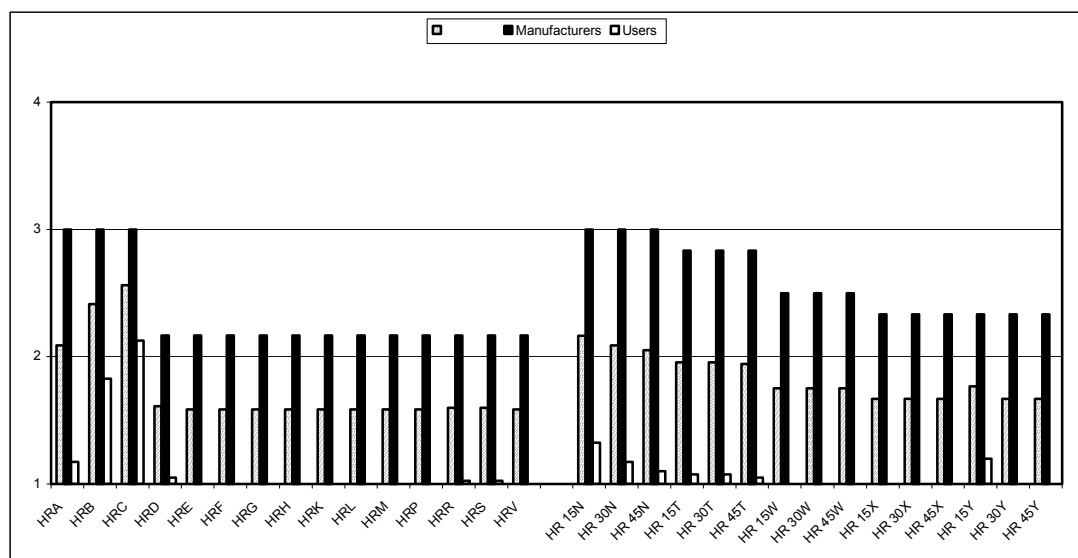


Figure 3. Analysis of the Rockwell and Superficial Rockwell hardness scales.

Similar to the Brinell results greater importance is placed on national traceability of both Rockwell and Superficial Rockwell hardness scales by the manufacturers of hardness machines and the suppliers of test blocks and indenters than the industrial user. Again, similar to the Brinell ratings, these results confirm the earlier consultative study [2] that of the Rockwell hardness scales HRC and HRB are the most important to the UK hardness industry. Of equal importance to the manufacturers of Rockwell hardness equipment is the HRA scale, although this scale was considered less important to the hardness user. The remaining Rockwell scales were all considered of equal importance to the manufacturers of hardness equipment, whereas only the HRD scale used for hardened and thin-sectioned steel, and HRR and HRS used for very soft plastics and rubbers were considered of any importance to the hardness user.

Of the Superficial Rockwell scales, the manufacturers of hardness equipment expressed diminishing importance in the HRN, HRT and HRW scales respectively. The HRX and HRY scales were considered as lower and of the same importance. By contrast the users expressed some limited importance of the HRN and HRT scales. The only other scale of importance was the HR 15Y scale used in the coating industry. In general, these results once again support the findings of [2].

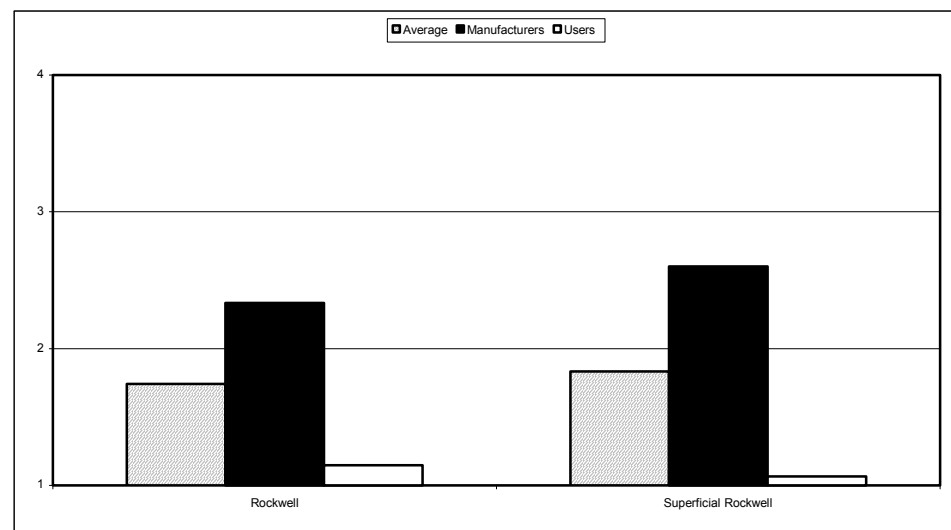


Figure 4. Comparison of Rockwell and Superficial Rockwell hardness scales.

Figure 4 illustrates the relative importance in Rockwell and Superficial Rockwell hardness. Surprisingly, the manufacturers considered that the Superficial Rockwell hardness scales are more important, this is due to the equal relative importance placed on the N, T, W, X, and Y scales. In contrast, the users considered that the Rockwell scales are the more important.

As may be expected, establishing the difference between hardmetal and hardened steel indenters for the Rockwell and Superficial Rockwell hardness scales was considered of greatest importance to the manufacturer of indenters and of least importance to the industrial user.

3.3 Vickers Hardness Scales

The replies for the relative importance of Vickers hardness scales are shown in Figure 5. For all scales, their importance is greater to the manufacturer of hardness equipment.

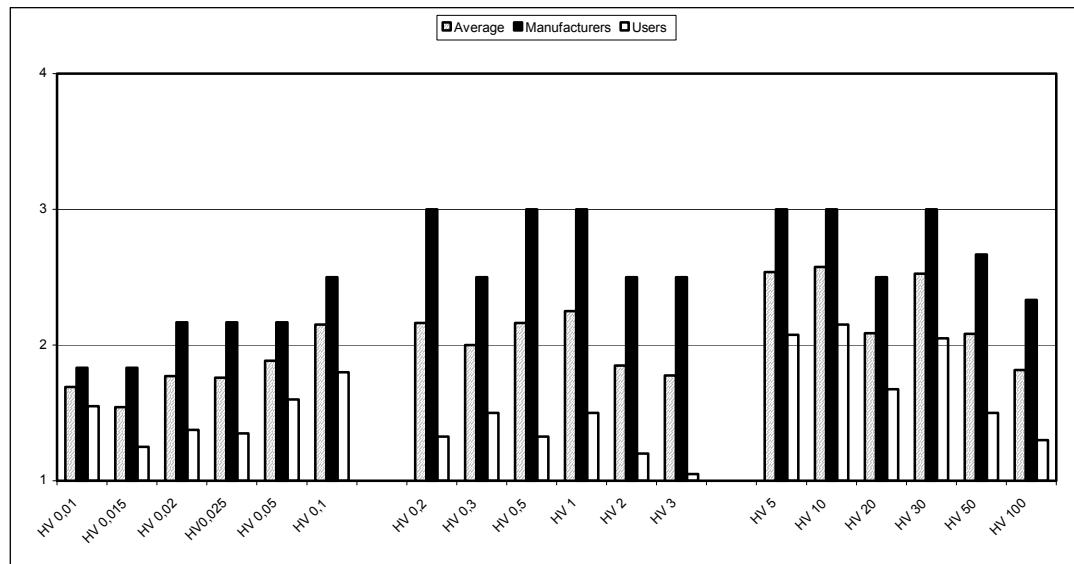


Figure 5. Analysis of the Vickers hardness scales.

Analysis of the Vickers hardness scales shows that the HV 10 and HV 30 scales were considered of highest importance - this concurs with the finding of the consultative study [2]. Of the macro-scales both the HV 5 and HV 20 scales were also considered important to the user. These scales were not considered of particular importance in [2], although this may be due to the user population surveyed rather than their increased usage. Several of the micro- and low force Vickers hardness scales were considered of high importance, both to the manufacturer and user. The relative importance of the micro-, low-force and macro-Vickers scales are summarised in Figure 6.

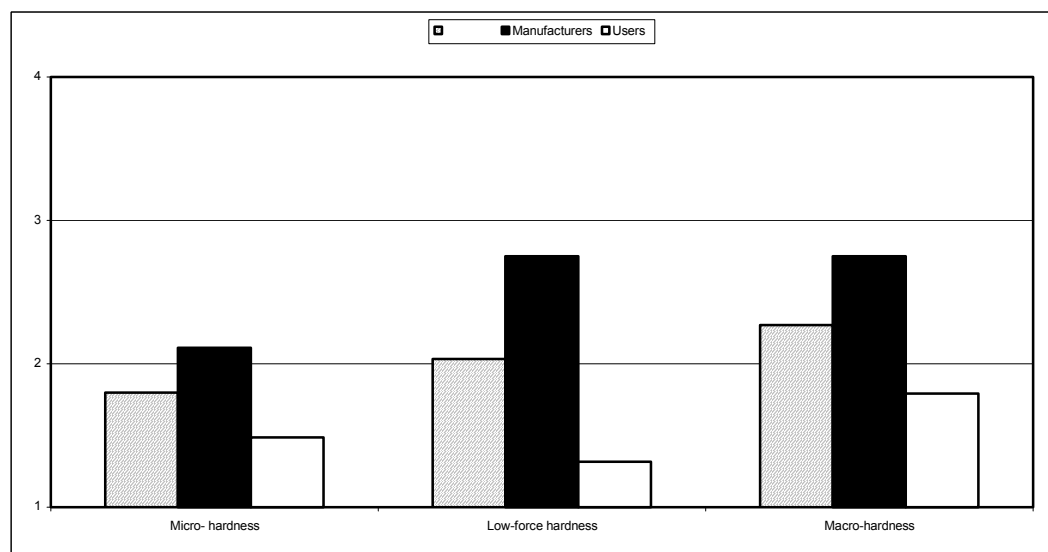


Figure 6. The relative importance of Vickers hardness scales.

This figure illustrates that to the manufacturer, both low-force and macro-Vickers are of equally high importance and greater than the importance of micro-Vickers. Whilst the user agrees with the importance of macro-Vickers the importance of micro-hardness is rated greater than the low-force Vickers hardness scales.

3.4 Summary of Indentation Hardness

Analysis of the importance of indentation hardness is summarised in Figure 7. This figure clearly shows the greater importance of traceable hardness scales to the manufacturer of hardness equipment, Brinell hardness being marginally of the greatest importance. The most important hardness scale to the user was Vickers hardness, although the most important single hardness scale was, not surprisingly, the Rockwell HRC scale.

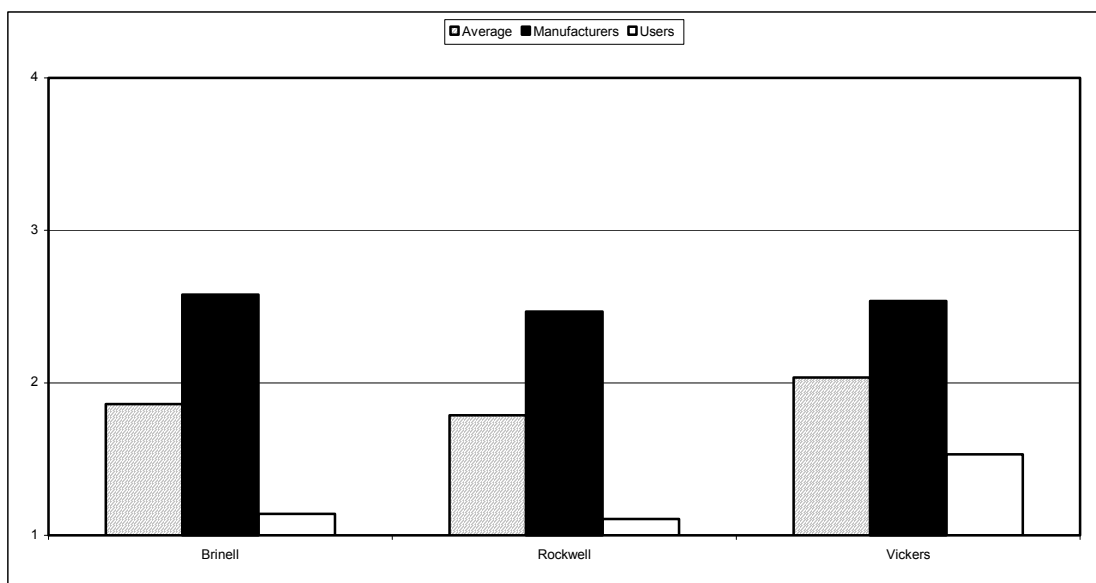


Figure 7. The overall importance of indentation hardness scales.

4 Elastomer/Polymer Hardness Scales

Despite the number of general enquiries on elastomer/polymer hardness test methods, in particular Shore test methods, received by NPL's hardness standards, and the increased usage of these techniques requiring greater accuracy [4] the overall importance was rated lowly (Figure 8).

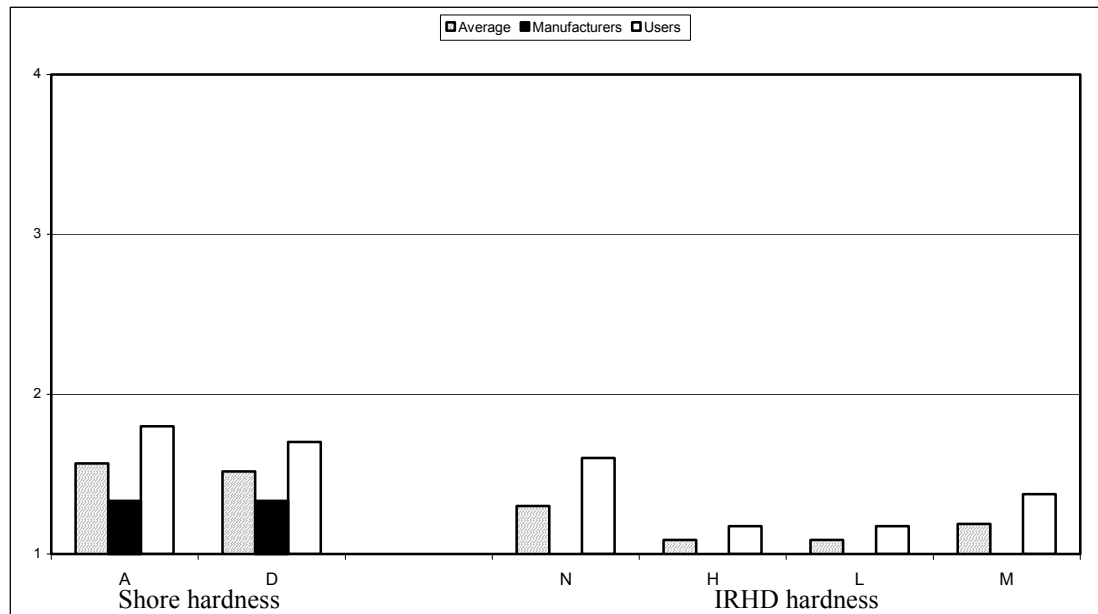


Figure 8. Analysis of the rubber hardness scales

The low rating is due to the relatively small population of organisations surveyed that carry out Shore and IRHD hardness testing, and it should be stressed that these organisations all considered the need for national traceability to these hardness scale to be of high importance.

5 Instrumented Indentation Hardness Scales

The importance of instrumented indentation hardness standards was only rated highly by those organisations that manufacture specialised hardness equipment for characterising thin films and the suppliers of specialist thin-coating. Of the more traditional manufacturers of hardness equipment the limited importance was expressed.

6 Conclusions and Further Work

A hardness survey of manufacturers and users of UK hardness equipment was carried out during June - August 2001 to identify the scale of importance of hardness scales. The findings of this survey supported the earlier consultative report [2] and Table 1 which lists the highest priority standards as used by UK industry. Support to these hardness scales was considered as the minimum requirement, by the UK hardness industry, and this survey has enabled the extension of hardness scales to be prioritised. The priorities for an increased range of hardness scales are presented below in Table 2. In this table the individual hardness scales have been prioritised according to the relative importance rating. Of these scales, only the Vickers hardness scales of HV 1 and below could not be supported by the present NPL CMAM

national hardness standard machines. However, support for Vickers hardness scales of HV 0,5 to HV 1 can be provided by MATC's micro-Vickers hardness machines at NPL.

Table 2. Priorities for increased range of hardness scales

	Scales	Nominal Force (N)
Brinell	HBW 2,5/62,5	612,9
	HBW 2,5/31,25	612,9
	HBW 5/250	2 452
	HBW 1/30	294,2
	HBW 2,5/15,625	153,2
	HBW 2,5/6,5	61,29
	HBW 1/10	9,807
Rockwell	HRA	588,4
	HRD	980,7
	HRR	588,4
	HRS	980,7
Superficial Rockwell	HR 15N, HR 45N	147,1 and 441,3
	HR 15T, HR 45T	147,1 and 441,3
Vickers	HV 5	49,03
	HV 0,3	2,942
	HV 1	9,807
	HV 0,2	1,961
	HV 0,5	4,903
	HV 0,1	0,980 7
	HV 0,05	0,490 3
	HV 50	490,3

It is also recommended that further work should be carried out to compare the hardness scales of hardmetal and hardened steel indenters to establish the scale relationship in the Rockwell and Superficial Rockwell hardness scales. Although the Brinell standard only specifies the use of hardmetal indenters, hardened steel balls will continue to be used in the manufacture of titanium and its alloys as tungsten carbide is considered a high-risk materials and can lead to production problems. It is therefore considered that a need exists to identify the scale relationship between Brinell hardmetal and hardened steel indenters.

Finally, this survey has indicated the need for knowledge transfer, particularly regarding hardness scales conversions and instrumented indentation hardness.

7 Acknowledgements.

The author of this report is grateful to the manufacturers and users of UK hardness equipment that replied to this hardness survey (Appendix 3) and also for the assistance of Mr Toby Farmer the secretary of the BSI hardness committee (ISE/NFE/4/5), Dr Ray Wilson of BMTA, Mr Trevor Steward of UKAS, and Ms Nicola Raymond the Manager of the NPL Mechanical Metrology Clubs, for help in disseminating the hardness survey to their members.

In addition, the author expresses his thanks to Dr Nigel Jennett and colleagues at NPL for assistance in constructing the questionnaire and its dissemination using their NPL MATC data base.

The hardness survey was funded by the National Measurement System Policy Unit of the Department of Trade and Industry.

8 References

- [1] Stanbury G and Davis F, Provision of hardness standards – Final Report, NPL Report CMAM 53, April 2000.
- [2] Budworth D W, Special study – NMS Programme Formulation 1996-99.
- [3] ISO/CD 14577 – 1, 2 & 3 : 1999, Metallic materials – Instrumented indentation test for hardness and other material properties, Draft document.
- [4] Stibler A, Herrmann K and Strobel P, Investigation of calibration methods for elastomer hardness testers. HARDMEKO '98, Sept 21 –23, 1998, Beijing. China.

Appendix 1: Background Notes on Hardness Scales

1 Introduction

Hardness is an unusual physical property in that it is the result of a defined measurement procedure and not an intrinsic materials property susceptible to precise definitions in terms of fundamental units of mass, length, and time. In practice, hardness is measured in terms of the size of an impression made on a specimen by an indenter of a specified shape when a specified force is applied for a specified time, the indent being measured after the force has been removed. There are three principal standard methods for expressing the relationship between hardness and the size of the impression, these being Brinell, Rockwell, and Vickers. For practical and calibration reasons, each of these methods is divided into a range of scales, defined by a combination of applied load and indenter morphology, to cover the range of hardness. Recently, with the introduction of instrumented indentation hardness, it has become possible to measure the indent under the applied force.

These background notes provide information on the following hardness methods:

- Brinell hardness
- Rockwell and Superficial Rockwell hardness
- Vickers hardness
- Elastomers/Polymers hardness
- Instrumented indentation for hardness and material properties.

2 Brinell hardness

In the Brinell hardness test [1] a ball indenter of diameter D is pressed into the surface of the test piece using a prescribed force F , and the diameter of the indentation d is measured after the force has been removed. The time for the initial application of the force is 2 s to 8 s, and the test force is maintained for 10 s to 15 s.

The Brinell hardness number is then the test force divided by the area of the indentation:

$$\begin{aligned} \text{HB} &= \text{Constant} \times \text{Test force} / \text{Surface area of indentation} \\ &= 0,102 \times 2F / \pi D \left(D - \sqrt{D^2 - d^2} \right) \end{aligned}$$

Recent revisions of hardness test methods [2] have provided amendments to the Brinell standard, these being:

- deletion of the hardened steel ball indenter, designated as HBS, and use of only a “hardmetal” tungsten carbide ball indenter, designated HBW
- deletion of the 2 mm ball indenter

The use of a tungsten carbide ball offers advantages to the life of the indenter, due to it being less likely to deform with repeated use, and gives improved repeatability. However, the actual measured hardness value may differ due to the change in tribological characteristics of the indenter/test block interface. Further work is required to characterise any change in the individual Brinell scales.

The deletion of the 2 mm ball does not influence the UK hardness industry and was made to bring the USA hardness standards in-line with the European standards.

Consultation of the standard [1] provides the complete list of the Brinell hardness scales, as shown in Table 1.

Table 1. Brinell hardness scales and test forces

Hardness scale	Ball diameter, D / mm	Nominal value of test force, F / N
HBW 10/3 000	10	29 420
HBW 10/1 500	10	14 710
HBW 10/1 000	10	9 807
HBW 10/500	10	4 903
HBW 10/250	10	2 452
HBW 10/100	10	980,7
HBW 5/750	5	7 355
HBW 5/250	5	2 452
HBW 5/125	5	1 226
HBW 5/62,5	5	612,9
HBW 5/25	5	245,2
HBW 2,5/187,5	2,5	1 839
HBW 2,5/62,5	2,5	612,9
HBW 2,5/31,25	2,5	306,5
HBW 2,5/15,625	2,5	153,2
HBW 2,5/6,25	2,5	61,29
HBW 1/30	1	294,2
HBW 1/10	1	98,07
HBW 1/5	1	49,03
HBW 1/2,5	1	24,52
HBW 1/1	1	9,807

3 Rockwell and Superficial Rockwell hardness

In the Rockwell and Superficial Rockwell hardness test [3] either a 120° diamond cone with a 0,2 mm radius spherical tip or a ball indenter of a specified diameter is pressed into the surface of the test piece using a two step application - an initial pre-force F_0 followed by an additional test force F_1 . For both tests the initial pre-force should be applied and maintained for a duration that shall not exceed 3 s. The increase in force from the pre-force condition to the total test force F should occur in no less than 1 s nor greater than 8 s. This force is then maintained for a duration of 4 s $\pm$ 2 s. The additional force is then removed and, while the pre-force is maintained, the reading is made after a short stabilisation time. The result of the test is read directly from the machine as:

$$HR = E - e$$

where: E = a constant dependent upon the indenter, and
 e = the permanent increase in penetration depth.

Table 2 lists the various Rockwell and Superficial Rockwell scales covered by the standard [3]. Also included in the table are additional Rockwell and Superficial Rockwell scales covered by the ASTM standard [4], the shading indicating these. The most common scales are Rockwell HRB and HRC and Superficial Rockwell HR30N and HR30T.

Table 2. Rockwell and Superficial Rockwell hardness scales and test forces

Scale	Indenter	Preliminary test force, F_0 / N	Total test force, F / N	Application
HRA	Diamond cone	98,07	588,4	Sheet steel: shallow case-hardened
HRB	Ball 1,587 5 mm dia.	98,07	980,7	Cu and Al alloys; annealed low C steels
HRC	Diamond cone	98,07	1 471	Hardened steels; cast irons, deep case-hardened
HRD	Diamond cone	98,07	980,7	Thin but hard steel; med. depth case-hardened
HRE	Ball 3,175 mm dia.	98,07	980,7	Cast iron; Al and Mg; and bearing metals
HRF	Ball 1,587 5 mm dia.	98,07	588,4	Annealed copper alloys; thin soft sheet materials
HRG	Ball 1,587 5 mm dia.	98,07	1 471	Malleable cast irons; phosphor bronze; gunmetals; Cu-Ni alloys
HRH	Ball 3,175 mm dia.	98,07	588,4	Soft materials; high ferritic alloys; Al; Pb; Zn
HRK	Ball 3,175 mm dia.	98,07	1 471	Al and Mg alloys
HRL	Ball 6,350 mm dia.	98,07	588,4	Thermoplastics
HRM	Ball 6,350 mm dia.	98,07	980,7	Thermoplastics
HRP	Ball 6,350 mm dia.	98,07	1 471	Thermosetting plastics
HRR	Ball 12,70 mm dia.	98,07	588,4	Very soft plastics and rubbers
HRS	Ball 12,70 mm dia.	98,07	980,7	-
HRV	Ball 12,70 mm dia.	98,07	1 471	-
HR 15N	Diamond cone	29,42	147,1	Range of hardness tests used when measuring the hardness of thin sheets, foils, coatings, surface heat treatments, and polymers including their surface treatments
HR 30N	Diamond cone	29,42	294,2	
HR 45N	Diamond cone	29,42	441,3	
HR 15T	Ball 1,587 5 mm dia.	29,42	147,1	
HR 30T	Ball 1,587 5 mm dia.	29,42	294,2	
HR 45T	Ball 1,587 5 mm dia.	29,42	441,3	
HR 15W	Ball 3,175 mm dia.	29,42	147,1	
HR 30W	Ball 3,175 mm dia.	29,42	294,2	
HR 45W	Ball 3,175 mm dia.	29,42	441,3	
HR 15X	Ball 6,350 mm dia.	29,42	147,1	
HR 30X	Ball 6,350 mm dia.	29,42	294,2	
HR 45X	Ball 6,350 mm dia.	29,42	441,3	
HR 15Y	Ball 12,70 mm dia.	29,42	147,1	
HR 30Y	Ball 12,70 mm dia.	29,42	294,2	
HR 45Y	Ball 12,70 mm dia.	29,42	441,3	

The hardness standards review [2] also considered the Rockwell scales A – K, N, and T, and where specified has allowed the use of a “hardmetal” tungsten carbide ball as the indenter as an alternative to a hardened steel ball indenter. As with Brinell hardness, the use of tungsten carbide ball indenters for Rockwell hardness requires further investigation to quantify the effect of indenter metallurgy on the resultant hardness scale.

4 Vickers hardness scales

In the Vickers hardness test [5] a diamond indenter, in the form of a square-based pyramid with an angle of 136° between the opposite faces at the vertex, is pressed into the surface of the test piece using a prescribed force F and, after the force has been removed, the diagonal lengths of the indentation d_1 and d_2 are measured. The time for the initial application of the force is 2 s to 8 s, and the test force is maintained for 10 s to 15 s. The Vickers hardness number HV is the test force

divided by the sloping (i.e. surface) area of the indenter up to a depth where it has the same cross-sectional area as the residual indent:

$$HV = \text{Constant} \times \text{Test force} / \text{Surface area of indentation}$$

$$= 0,102 \times 2F \left(\sin \frac{136^\circ}{2} \right) / d^2$$

where: d = arithmetic mean, in mm, of the two diagonal lengths d_1 and d_2

Table 3 provides a list of the Vickers hardness standard scales.

Table 3. Vickers hardness scales and test forces

Micro-hardness scales	Test force F / N
HV 0,01	0,098 07
HV 0,015	0,147 1
HV 0,02	0,196 1
HV 0,025	0,245 2
HV 0,05	0,490 3
HV 0,1	0,980 7
Low-force hardness scales	
HV 0,2	1,961
HV 0,3	2,942
HV 0,5	4,903
HV 1	9,807
HV 2	19,61
HV 3	29,42
Macro-hardness scales	
HV 5	49,03
HV 10	98,07
HV 20	196,1
HV 30	294,2
HV 50	490,3
HV 100	980,7

5 Elastomers/Polymers hardness

The standard methods for measuring the hardness of elastomers and polymers use either Shore A and D or the IRHD methods N, H, L, and M; these test methods are specified in ISO 868 [6] and BS 903/ISO 48 [7] respectively. The increased usage of these hardness techniques has resulted in a requirement for greater accuracy [8].

5.1 Shore hardness

Shore hardness specifies methods for determining the hardness of materials by means of durometers of two types: type A for softer materials and type D for harder materials [6], although the ASTM standard [9] covers eight types of durometer scales. The method permits measurement of the initial indentation, the indentation after a specified period of time, or both. The indentation hardness is inversely related to the penetration and is dependent on the modulus of elasticity and the viscoelastic properties of the material. The shape of the indenter, the force applied, and the test duration influence the results obtained. The Shore durometer consists of a reference presser foot, an indenter, an indicating device, and a calibrated spring that applies the force to the indenter. The difference between the type A and type D durometer is in the shape of the indenter and the calibrated spring (Table 4).

Table 4. Shore hardness scales and test forces

Shore durometer	Indenter	Applied force, F / mN
Type A	Hardened steel rod 1,10 mm – 1,14 mm dia, with a truncated 35° cone, 0,79 mm dia.	$F = 550 + 75 H_A$
Type D	Hardened steel rod 1,10 mm – 1,14 mm dia, with a 30° conical point, 0,79 mm dia	$F = 445 H_D$

Note: It is recommended that measurements be made with the type D durometer when the value is above 90 H_A , and with a type A durometer when the value is less than 20 H_D .

The units of hardness range from 0 for the full protrusion of the 2,50 mm indenter to 100 for nil protrusion. The force is applied as rapidly as possible, without shock, and the hardness reading made after a duration of $15 \text{ s} \pm 1 \text{ s}$. If an instantaneous reading is specified, the scale is read within 1 s of force application. There is no simple relationship between results obtained with one type of durometer and those obtained with either another type of durometer or another instrument for measuring hardness.

5.2 IRHD hardness

IRHD (International Rubber Hardness Degrees) provides four methods for the determination of the hardness of vulcanised or thermoplastic rubber surfaces (N, H, L, and M) and four methods for the determination of the apparent hardness of curved surfaces (CN, CH, CL, and CM). The test consists of measuring the difference between the depths of indentation of a ball into a rubber surface under a small initial contact force followed by a large total test force. The methods differ primarily in the diameter of the indenting ball and the magnitude of the indenting force selected according to the hardness of the rubber (Table 5).

Table 5. IRHD hardness scales and test forces

Test method	Diameter of indenter, / mm	Contact force, / N	Additional force, / N	Total force, / N	Application
N	2,50 ± 0,01	0,30 ± 0,02	5,40 ± 0,01	5,70 ± 0,03	Thickness: = 4 mm, Range: 35 – 85 IRHD, or 30 – 95 IRHD
H	1,00 ± 0,01	0,30 ± 0,02	5,40 ± 0,01	5,70 ± 0,03	Thickness: = 4 mm, Range: 85 – 100 IRHD
L	5,00 ± 0,01	0,30 ± 0,02	5,40 ± 0,01	5,70 ± 0,03	Thickness: = 6 mm, Range: 10 – 35 IRHD
M	0,395 ± 0,005	0,008 3 ± 0,000 5	0,145 ± 0,000 5	0,153 3 ± 0,001	Thickness: < 4 mm, Range: 35 – 85 IRHD, or 30 – 95 IRHD

Note: Hardness values obtained for method N within the ranges 85 – 95 IRHD and 30 – 35 IRHD may not agree with the values obtained for method H or method L, respectively.

The relationship between the indentation depth D , the hardness of the rubber, and the IRHD number is based on:

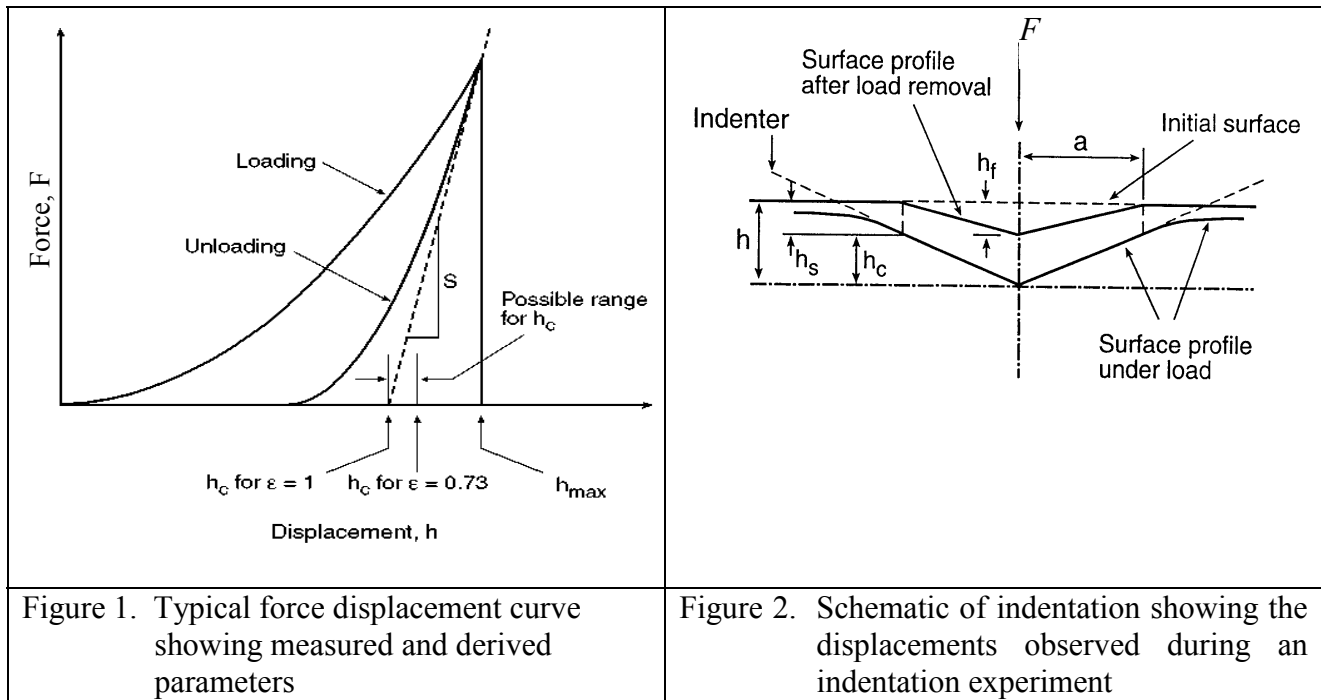
$$\frac{F}{E} = 0,0038 r^{0,65} x D^{1,35}$$

where: F = indentation force, in N
 r = radius of the indenter, in mm
 E = Young's modulus, in MPa

From the value of Young's modulus and using the relevant 'look-up' curve, the IRHD value can be read. These hardness scales are chosen such that a 0 IRHD value represents the hardness of a material with a zero Young's modulus and 100 IRHD represents the hardness of a material with an infinite Young's modulus.

6 Instrumented indentation for hardness and material properties

Hardness has conventionally been defined as the resistance of a material to permanent penetration by another harder material with measurement being made after the test force has been removed, such that elastic deformation is ignored. Instrumented indentation hardness [10] provides the ability to measure the indenter penetration h under the applied force F throughout the testing cycle and is therefore capable of measuring both the plastic and elastic deformation of the material under test. Figure 1 is a typical load displacement hysteresis curve obtained from an elastic / plastic material and Figure 2 shows the schematic representation of the indent under load and in the unloaded condition. Apart from the measurement of the indenter penetration under the applied force, the unloading contact compliance C ($= 1/S$) and the contact depth h_c can be calculated. The value of h_c is dependent on the exact shape of the indenter and material response to the indentation; 'sinking-in' and 'piling-up' around the indenter also affect the value.



Instrumented indentation is therefore able to determine the stiffness of the contact and thus the indentation modulus E_{IT} as well as the indentation hardness H_{IT} (equivalent to Meyer Hardness and similar to HV for a Vickers indenter) and the Martens hardness HM (previously known as Universal hardness, HU) of a material. In addition, this technique enables time-dependent material properties, such as the ratio of elastic to plastic work done during an indentation, to be defined.

Table 6 reproduces from the draft standard the three scale ranges covered.

Table 6. Instrumented indentation hardness scale ranges and test forces

Scale	Force/indentation depth
Macro range	$2 \text{ N} < F < 30\,000 \text{ N}$
Micro range	$2 \text{ N} > F \text{ and } h > 0,000\,2 \text{ mm}$
Nano range	$0,000\,2 \text{ mm} \geq h$

HM is defined only for Vickers and Berkovich indenters, as shown below. However, in the draft standard [10], a wide range of other materials properties calculable from instrumented indentation data is defined for a wide range of indenter geometries: cube corner, Knoop or ball indenters (including “hardmetal” ball indenters with diameters ranging from 0,5 mm to 10 mm), and diamond sphero-conical indenters with the range of flank angles α of 30°, 45°, and 90°, and radius of curvature varying from $0,500 \text{ mm} > R > 0,050 \text{ mm}$.

6.1 Martens hardness scale

The Martens hardness value is calculated by dividing the test force F by the surface area of the indenter penetrating beyond the original surface of the test piece $A_s(h)$:

a) Vickers indenter

$$HM = \frac{F}{A_s(h)} = \frac{F}{26,43 \cdot h^2}$$

b) Berkovich indenter

$$HM = \frac{F}{A_s(h)} = \frac{F}{26,44 \cdot h^2}$$

6.2 Indentation hardness scale

The indentation hardness H_{IT} is calculated from the test force, F , divided by the projected area of the indenter in contact with the test piece at maximum load:

$$H_{IT} = \frac{F}{A(h_c)}$$

The projected contact area $A(h_c)$ is calculated from knowledge of the geometry of the indenter and the stiffness of the contact [10]. In many materials, the area of contact under moderate forces is a good approximation to that which remains when the indenter is fully unloaded and removed from the surface. In such cases, the indentation hardness is very similar to Vickers hardness, the exceptions being that the indentation area is calculated from measured displacement data instead of optical measurement and that the Vickers scale assumes a perfect geometry whereas instrumented indentation uses a measured shape of the indenter which makes allowance for tip rounding and other common deviations. In practice, tip rounding means that the two scales diverge as the indentation contact becomes more elastic until, at the elastic limit, HV becomes infinite and H_{IT} ceases to be a measure of plasticity.

6.3 Indentation modulus

The indentation modulus E_{IT} is calculated from the slope of the unloading curve through the formula:

$$E_{IT} = (1 - \nu_{IT}^2) \left/ \left\{ \frac{2}{\sqrt{\pi}} \cdot \frac{\sqrt{A(h_c)}}{S} - \frac{(1 - \nu_{indenter}^2)}{E_{indenter}} \right\} \right.$$

where: ν_{IT} = the Poisson's ratio of the test piece

$\nu_{indenter}$ = the Poisson's ratio of the indenter

S = the slope of the tangent of the force/indentation curve during the unloading cycle (Figure 1)

h_c = the contact depth value, which is dependent on the shape of the indenter (Figure 2)

The full procedure for this is described in the draft standard [10]. For homogeneous and isotropic materials, E_{IT} approaches the Young's modulus of the material. For an isotropic material, the value is a 3D average of the crystallographic moduli.

7 References

- [1] BS EN ISO 6506 - 1, 2 & 3 : 1999, Metallic materials -Brinell hardness test.
- [2] Minutes of meeting ISO/TC 164 N235 “Hardness testing of metals” circulated by BSI ISE/NFE/4/5, 21//8/2000.
- [3] BS EN ISO 6508 - 1, 2 & 3 : 1999, Metallic materials -Rockwell hardness test.
- [4] ASTM E18-00, Standard test methods for Rockwell hardness and Rockwell Superficial hardness of metallic materials.
- [5] BS EN ISO 6507 - 1, 2 & 3 : 1998, Metallic materials -Vickers hardness test.
- [6] ISO 868 : 1985, Plastics and ebonite – Determination of indentation hardness by means of a Durometer (Shore hardness).
- [7] BS 903 : Part A26 : 1995, Physical testing of rubber. Method for determination of hardness (hardness between 10 IRHD and 100 IRHD).
- [8] Stibler A, Herrmann K and Strobel P, Investigation of calibration methods for elastomer hardness testers. HARDMEKO '98, Sept 21 –23, 1998, Beijing. China.
- [9] ASTM D2240-00, Standard test method for rubber properties – Durometer hardness A, B, C, D, DO, OO and M.
- [10] ISO/CD 14577 - 1, 2 & 3 : 1999, Metallic materials - Instrumented indentation test for hardness and other material properties, Draft document.

Appendix 2: HARDNESS QUESTIONNAIRE

Please complete and return by 8 June 2001 to:

Dr Francis Davis
Project Manager – Torque and Hardness Standards
Centre for Mechanical and Acoustical Metrology
National Physical Laboratory
Queens Road
Teddington
TW 11 0LW

OR

Respond by Fax on: 020 8943 6184,
or E-mail: francis.davis@npl.co.uk

This hardness questionnaire seeks to gather information about the current and future importance of hardness and instrumented indentation for hardness and material properties to your organisation.

The questionnaire is in three sections:

- Section 1** asks for details on your organisation
- Section 2** relates to your in-house hardness test equipment
- Section 3** seeks opinions as to the relative importance of hardness scales

This questionnaire provides a chance to contribute towards the further development of the UK hardness standards. From the returned questionnaires and analysis, an NPL report on the priorities for increasing the range of hardness scales will be published and disseminated to all respondents by the end of June 2001.

I thank you in advance for your assistance.

Section 1 – Your Organisation

Company:
Address:

Contact:
Job Title:
Tel No:
Fax No:
E-mail:

Hardness Sector: (Please tick all that apply)	Conventional hardness	Instrumented indentation
Manufacturer of hardness machines	☐	☐
User of hardness machines	☐	☐
UKAS accredited laboratory	☐	☐
Non-UKAS laboratory	☐	☐
Manufacturer of hardness ancillary equipment	☐	☐
Other –please state	☐	☐

Section 2 – Hardness equipment and scales used in your organisation

Do you have existing hardness equipment?	Yes	No
Type of hardness equipment and manufacturer		
Brinell	Yes	No
Rockwell	Yes	No
Vickers	Yes	No
Non-metallic	Yes	No
Instrumented indentation	Yes	No
Others (Please state)		

Section 3 – Importance of hardness scales

This section relates to the importance of national traceability for the various hardness scales to your organisation (1 = unimportant, 4 = very important). It would also be useful if you could provide information on the application of the hardness scales within your organisation.

BRINELL HARDNESS SCALES

Scales	Used at present	Importance				Application of scale to your organisation		
HBW 10/3 000		1	2	3	4			
HBW 10/1 500		1	2	3	4			
HBW 10/1 000		1	2	3	4			
HBW 10/500		1	2	3	4			
HBW 10/250		1	2	3	4			
HBW 10/100		1	2	3	4			
HBW 5/750		1	2	3	4			
HBW 5/250		1	2	3	4			
HBW 5/125		1	2	3	4			
HBW 5/62,5		1	2	3	4			
HBW 5/25		1	2	3	4			
HBW 2,5/187,5		1	2	3	4			
HBW 2,5/62,5		1	2	3	4			
HBW 2,5/31,25		1	2	3	4			
HBW 2,5/15,625		1	2	3	4			
HBW 2,5/6,25		1	2	3	4			
HBW 1/30		1	2	3	4			
HBW 1/10		1	2	3	4			
HBW 1/5		1	2	3	4			
HBW 1/2,5		1	2	3	4			
HBW 1/1		1	2	3	4			
Is establishing the difference between “hardmetal” and hardened steel indenters important to you?								
						<table border="1"> <tr> <td>YES</td> <td>NO</td> </tr> </table>	YES	NO
YES	NO							

Comments – Please provide any supporting statement on the commercial importance of the above scales to your organisation.

Section 3 – Importance of hardness scales (continued)

ROCKWELL AND SUPERFICIAL ROCKWELL HARDNESS SCALES

Scales	Used at Present	Importance				Application of scale to your organisation		
HRA		1	2	3	4			
HRB		1	2	3	4			
HRC		1	2	3	4			
HRD		1	2	3	4			
HRE		1	2	3	4			
HRF		1	2	3	4			
HRG		1	2	3	4			
HRH		1	2	3	4			
HRK		1	2	3	4			
HRL		1	2	3	4			
HRM		1	2	3	4			
HRP		1	2	3	4			
HRR		1	2	3	4			
HRS		1	2	3	4			
HRV		1	2	3	4			
HR 15N		1	2	3	4			
HR 30N		1	2	3	4			
HR 45N		1	2	3	4			
HR 15T		1	2	3	4			
HR 30T		1	2	3	4			
HR 45T		1	2	3	4			
HR 15W		1	2	3	4			
HR 30W		1	2	3	4			
HR 45W		1	2	3	4			
HR 15X		1	2	3	4			
HR 30X		1	2	3	4			
HR 45X		1	2	3	4			
HR 15Y		1	2	3	4			
HR 30Y		1	2	3	4			
HR 45Y		1	2	3	4			
Is establishing the difference between “hardmetal” and hardened steel indenters important to you?						<table border="1"> <tr> <td>YES</td> <td>NO</td> </tr> </table>	YES	NO
YES	NO							

Comments – Please provide any supporting statement on the commercial importance of the above scales to your organisation.

Section 3 – Importance of hardness scales (continued)**VICKERS HARDNESS SCALES**

Micro-hardness scales	Used at present	Importance				Application of scale to your organisation
HV 0,01		1	2	3	4	
HV 0,015		1	2	3	4	
HV 0,02		1	2	3	4	
HV 0,025		1	2	3	4	
HV 0,05		1	2	3	4	
HV 0,1		1	2	3	4	
Low-force hardness scales						
HV 0,2		1	2	3	4	
HV 0,3		1	2	3	4	
HV 0,5		1	2	3	4	
HV 1		1	2	3	4	
HV 2		1	2	3	4	
HV 3		1	2	3	4	
Macro-hardness scales						
HV 5		1	2	3	4	
HV 10		1	2	3	4	
HV 20		1	2	3	4	
HV 30		1	2	3	4	
HV 50		1	2	3	4	
HV 100		1	2	3	4	

Comments – Please provide any supporting statement on the commercial importance of the above scales to your organisation.

Section 3 – Importance of hardness scales (continued)**RUBBER HARDNESS SCALES**

Shore hardness	Used at present	Importance				Application of scale to your organisation
A		1	2	3	4	
D		1	2	3	4	
IRHD hardness						
N		1	2	3	4	
H		1	2	3	4	
L		1	2	3	4	
M		1	2	3	4	

Comments – Please provide any supporting statement on the commercial importance of the above scales to your organisation.

INSTRUMENTED INDENTATION HARDNESS

	Used at present	Importance				Application
Macro-scale ($2\text{ N} < F < 30\,000\text{ N}$) HM H _{IT} E _{IT} Others (Please state below)		1	2	3	4	
		1	2	3	4	
		1	2	3	4	
		1	2	3	4	
		1	2	3	4	
Micro-scale ($2\text{ N} > F$ and $h > 0,000\,2$) HM H _{IT} E _{IT} Others (Please state below)		1	2	3	4	
		1	2	3	4	
		1	2	3	4	
		1	2	3	4	
		1	2	3	4	
Nano-scale ($h \leq 0,000\,2\text{ mm}$) HM H _{IT} E _{IT} Others (Please state below)		1	2	3	4	
		1	2	3	4	
		1	2	3	4	
		1	2	3	4	
		1	2	3	4	

Comments - Please indicate other material properties of interest and provide any supporting statement on the commercial importance of the above scales to your organisation.

Appendix 3: Organisations that Responded to the NPL Hardness Survey

Advanced Elastomer Systems.	McLaren International Limited.
AEA Technology Plc.	Mettis Aerospace Group.
Asams Limited.	Micro Materials Limited.
Association of Tank & Cistern Manufacturer.	Monitor Coatings and Engineers Limited.
Allvac Ltd. – Commercial Testing Services.	Morgan Advanced Ceramics
Balmoral Group Limited.	Morgan Materials Technology Limited.
Barton Cold-Form Limited.	NSK European Technology Centre.
Becker Industrial Coatings Limited.	Pilkington Plc.
BHR Group Limited.	Plasma Coatings Limited.
Bodycote Heat Treatments.	Power Technology Centre, Powergen.
C & D Technologies (NCL) Limited.	Quality Castings (Slough) Limited.
Caledonian Medical Limited.	Sandawana Castings Limited.
Coating Technology and Alloys Limited.	Snamprogetti Limited.
Cobham Composites Limited.	SPS Technologies.
Cogent Defence Systems.	St Clair (Polymers) Limited.
Corus UK Limited.	Resintech Limited.
Cranfield University.	Rolls-Royce Plc.
CV Instruments (Part of Bowers Metrology).	TARRC.
Defence Aviation Repair Agency.	Teer Coatings Limited.
Dowty Engineered Seals Limited.	Tenmat Limited.
Denso Marston Limited.	The Hymatic Engineering Company Limited.
Euro Products Limited.	The University of Leicester.
Firth Rixon Rings Limited.	The University of Sheffield.
Foundrax Engineering Products Limited.	Thorton Precision Components Limited.
Hexcel Composite Limited.	Timet UK Limited.
H. C. Starck Limited.	Triplex Foundry Limited.
H & S Aviation Limited.	TRW Automotive Technical Centre.
HT Consultants.	Unilever.
Hoerbiger Rings and Packings Limited.	Uponor Limited.
Holo Krome Limited.	Urenco (Capenhurst) Limited.
Imperial College.	Williams F1.
Incotest (Special Metals Wiggin Limited).	
Indentec Hardness Testing Machines Limited.	
Industrial Research and Technology Unit.	
Instron Limited.	
Intertek Testing Services (Leicester) Limited.	
James Walker & Co. Limited.	
Jay Engineering Consultancy Limited.	
Kvaerner Oil & Gas.	
Kiveton Park Steel Limited.	
Kohler Mira Limited.	
Leslie Group Limited.	
Metaltech Consulting Services.	