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CHARACTERIZING ROCKWELL DIAMOND INDENTERS USING DEPTH OF PENETRATION

Robert Ellis, Paul Mumford, Sam Low, Andy Knott

David L. Ellis Company, Inc., Acton, MA, USA
United Testing, Huntington Beach, CA, USA
NIST, Gaithersburg, MD, USA
National Physical Laboratory (NPL), Teddington, United Kingdom

Abstract – Diamond indenters used in a Rockwell hardness tester can dramatically affect the performance of the test. For this reason, it is important to find a method that can characterise the indenter. Current methods of verifying diamond indenter geometry have failed to thoroughly predict the performance when in use in the Rockwell tester. The paper addresses a possible method to use depth data during the test to characterise the indenter.

Keywords: hardness, indenters, depth

1. INTRODUCTION

All Rockwell diamond indenters appear to have a permanent bias that can change hardness numbers through its use versus another diamond indenter. In effect, if all the other parameters of the Rockwell test remain the same, a simple change of the diamond indenter will change the hardness values. If one looks at Fig. 1, it shows that with the proper equipment, depths of indenter travel can be measured during the Rockwell test, and plotted to show the differences between the indentation processes of several indenters. These differences become very noticeable when using a directly verified closed-loop tester having good repeatability in the application of the test forces and time cycles.

It is not the absolute value of the hardness obtained from the indenter that becomes important but rather the relative difference from one indenter to another. Absolute hardness value differences can be attributed to different hardness test systems by comparing one tester against another. The contention here is that the differences found for one indenter versus the other should be the same regardless of which Rockwell test system they are used on.

Ideally, the procedure used to characterise the indenters should be easy to use. This means that; (1) the technique should be simple for others to follow, (2) the basic method used should remain the same regardless of the test system employed and (3) the results should be able to be used and interpreted by all users.

Another consideration is the elimination of the flaws found in the Rockwell test that normally would affect the results. Using the method of depth, flaws such as elastic and plastic deformation of the tester are taken out of the results.

Final results show the differences of one indenter relative to another. They can be shown on any Rockwell diamond hardness scale and at any hardness level. In cases such as the HRC scale, the results shown can give an indication of performance on others scales that use lower test forces. This is because the depths of the HRC scale include areas of the diamond indenter used in other scales such as HR15N where only the tip of the indenter is used.

Current practices during direct verification cannot completely characterise the Rockwell diamond indenter. In effect, it is much like measuring a balloon with string. Very little of the indenter surface is measured. The usual six or eight ways across are not sufficient. Using the depth method, all of the contact area of the indenter is taken into account. The effect of lobes or surface finish of the indenter will be transparently shown in the results. Ordinarily, this effect cannot be quantified during the direct verification of the indenter using geometry.

It has been shown that indenter geometry can greatly influence measured hardness values [1]. While direct verification for indenter geometry does not absolutely qualify an indenter, it still must be performed in order to find candidates for good performance during indirect verification.

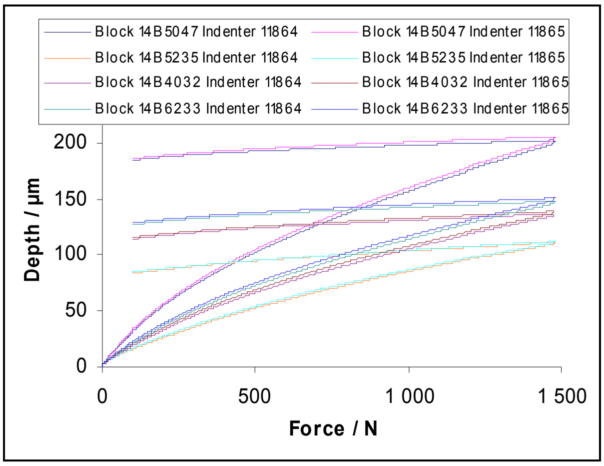

Fig. 1. Indenter depths during Rockwell HRC tests

Finally, this method also gives a hardness value for performance. In the Rockwell test, only the final depth value is used when calculating a Rockwell hardness number. With the advent of closed-loop directly verified Rockwell hardness testers, all of the force, depth and time values can be recorded during the test. Both performance in hardness values and indenter characteristics are obtained at the same time.

2. EQUIPMENT AND STANDARDS USED

The following describes the indenters, test blocks, and testers that were used in the study.

2.1. Indenters

The Rockwell indenters used during this study were produced at three accredited diamond indenter manufacturing facilities. All were directly verified for geometry and also measured for indirect verification through Rockwell hardness tests on the HRC scale and, in one case, by the National Physical Laboratory (NPL), Teddington, UK and David L Ellis Company, on the HR15N and HR45N Rockwell scales.

The geometry of all indenters met the requirements of the international Rockwell hardness test method standards of ASTM International (E 18) [2] and the International Organization for Standardization (ISO 6508) [3]. Indenter 40222 was chosen for the test because it had cone and angle values to the extreme of the allowable tolerances. It was hoped that the depth curves would help explain previous studies where this indenter was used [1]. Table 1 gives the geometries determined for the indenters.

Table 1. Measured indenter parameters

Serial Number	Cone Angle / °	Tip Radius / µm
S3581	120.011 ± 0.017	199.2 ± 1.19
ST11864	120.017 ± 0.017	203.0 ± 3.00
ST11865	119.983 ± 0.017	200.0 ± 3.00
1922	119.880 ± 0.020	198.8 ± 3.00
40222	120.244 ± 0.020	191.5 ± 3.00
The above uncertainties are at a 95 % level of confidence		

Only indenters ST11864 and ST11865 were verified for performance at both primary facilities: the National Institute for Standards and Technology (NIST) and the National Physical Laboratory (NPL). They were also compared at the David L. Ellis Company (Ellis Co.). They are the common measurements for all the indenters, test blocks and facilities. Indenter S3581 was compared with ST11864 and ST11865 at NIST only. Indenters 1922 and 40222 were compared only at NPL with ST11864 and ST11865.

Initial indenter comparisons began at NIST when indenters ST11864 and ST11865 were indirectly verified against the NIST indenter S3581. Indenter S3581 has been used at NIST to calibrate reference test blocks. Test values can be seen in Table 2 and are plotted in Fig. 2..

Table 2. NIST indirect verification data

HRC	S3581 (1)	ST11864	ST11865	S3581 (2)
25.00	25.17	25.22	25.56	25.29
45.00	44.90	44.94	45.28	44.96
63.00	63.95	63.81	63.92	63.94

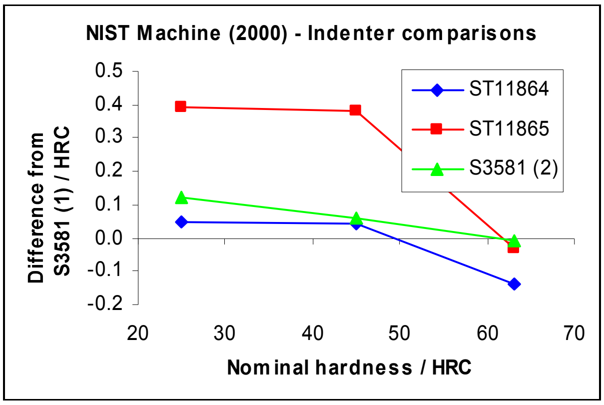

Fig. 2. NIST data uncertainties without accounting for bias in indenters are no worse than ±0.1 HRC at a 95 % level of confidence

It has been found since the NIST comparison that indenters ST11864 and ST11865 maintain their offset over time regardless which tester is used. Most notably, ST11865 always reads higher than ST11864 on the middle to low end of the HRC scale. This has held the same since the NIST comparison through testing at Ellis Co. and NPL.

2.2 Reference blocks.

All hardness reference block standards degrade (or drift) over time so it is not possible to use the reference blocks forever. However, test block reference standards should be used as long as the hardness level remains the same and indents can be made the required distance apart.

The original comparisons at NIST of S3581, ST11864, and ST11865 were conducted on NIST reference blocks in the year 2000. They were not used again in this study. Later in 2004, test values which included force and depth were obtained from NIST that were recorded during the 2000 indenter comparisons (Fig. 2).

For the 2004 indenter comparisons at Ellis Co. and NPL, a set of standards at 60 HRC (nominal), 45 HRC (nominal) and 25 HRC (nominal) scale were used. Also, one set had a 55 HRC (nominal), 90 HR15N (nominal) and 45 HR45N (nominal).

2.3. Hardness testers

The equipment used included a secondary Rockwell hardness calibration machine at Ellis Co. and two primary hardness testers at NIST and NPL.

All of the hardness testers used were directly verified (for force and depth) as defined by ASTM E 18 [2] and ISO 6508 [3]. They are considered closed loop testers allowing that the nearly exact dwell times could be duplicated on all three testers. Also, the testers used the same test cycles of 3 s preliminary force dwell time 5 s total force dwell and 4 s recovery dwell time.

All three testers used a similar method to attach the indenter. The method of attachment to the entire tester was firm and not of the slip fit type. It was felt that slip methods could be a source of error.

The NIST tester had the capability to capture the depth measurement values over the whole test time; however, it was not programmed to report them in even force increments. It should be noted that these tests were conducted in 2000 at NIST when continuous force/ depth values were not a concern. The explanation for this is the height of the spreadsheet columns were different every test. This made it impossible to simply line up one column with another without managing the data. As a result, there was a need to interpolate values. Once this had occurred, the data appeared choppy (see Fig. 3).

The secondary machine at Ellis Co. had a unique program written to capture the force, depth and time value. At first raw data and uneven listing of forces made it extremely difficult to compare the indenters. Again, another program was written in which only even force values were shown. This made comparisons easier. This machine did have a flaw in that the elevating screw could be moved. Despite this issue, the tester did show values that indicated diamond indenters could give different depths (Fig. 4).

The NPL machine gave the least choppy data. At this point, it had been determined what method of reporting the data should be used. Again, the data appeared to support the premise that different indenters give different depth values.

After several attempts at NPL, the data fields were set so that it became easy to work with the data at a later time, using even intervals of force and comparing the differences between incremental and decremental depth readings for indenter pairs. If further studies were to be made, this would be the model for future data compilation. The depth curves shown here are the final results (see Figs. 5 to 10).

For each indenter, the difference between the measured depth under an increasing force and the measured depth under the same decreasing force was calculated, at a large number of specific forces across the force range applied. This gave a measure of the 'plastic' deformation caused by the indenter at each force. To compare indenters, the difference between the two values of 'plastic' deformation was calculated at each specific force, and plotted against force.

3. PROCEDURE

3.1 General procedure

The reference blocks were tested as per ASTM E 18 [2] and ISO 6508 [3]. Six tests were performed over the surface of each test block for the given scale and hardness range. During these tests, all data of force, depth and hardness values were recorded. The average of the hardness measurements was calculated to reduce the effect of hardness non-uniformity of the block.

The same reference blocks were used with two or more indenters on the same machine. In this way, the variations of depth and hardness numbers could be determined between different indenters.

It must be stated that the curves were normalized to pre-load. All data began at the end of the set pre-load time of three seconds.

3.2. Equations

Since the differences in depth are very slight between the indenters with respect to the total indentation depths, it is necessary to compare the differences in depth. Once these are calculated, the comparisons become much more dramatic. The lines appear too close as seen in Fig. 1 if the differences in depths are not considered. As shown in equation 1, the depth data from one indenter for each block and tester combination was chosen as a reference. After that, the data from other indenters are compared against the data.

$$\text{Compared depth} = \text{Depth Reference} - \text{Depth Other} \quad (1)$$

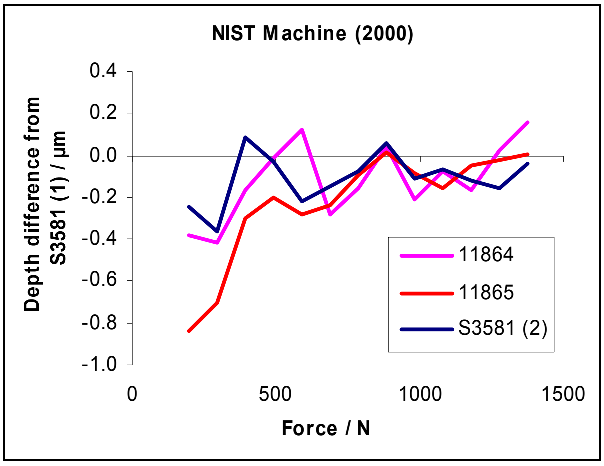

Fig. 3. Depth comparisons on primary tester in 2000 - indenters ST11864 and ST11865 compared to S3581

4. DISCUSSION

4.1. Interpreting the data.

There was a significant difference in depth from one indenter to another. It can be seen that in some cases, it is as much as 2 µm between indenters. In the case of indenters ST11864 and ST11865, the depth difference between indenters appears to remain the same regardless of which tester or test blocks are used.

There can be some comparisons between the other scales and hardness ranges. Since the HRC tests include similar indenter exposure to the block as HR15N scale; the beginning of the curve at HRC is also similar to the HR15N.

A reference indenter is chosen to be the standard. After that, any indenter that produces depth curves that are flat relative to the standard, are similar in performance to the standard. Those indenters that produce depth curves significantly above or below the standard indenter are those that will not perform as well as the standard indenter.

The first comparisons use the NIST indenter S3581 as the reference, as shown in Fig. 2. This provides the basis of the performance difference between indenters ST11864 and ST11865. It was found that ST11865 read higher than

Table 3. Measured hardness values at Ellis Co. and NPL

	Laboratory	Ellis Co.	NPL	Ellis Co.	NPL	NPL	NPL
	Indenter	ST11864		ST11865		1922	40222
Range	**Block**						
HRC	14B5047	23.96	24.10	24.29	24.22	24.70	25.25
	14B6233	47.07	47.26	47.24	47.29	47.72	48.15
	14B4032	52.36	52.56	52.64	52.47	53.09	53.28
	14B5235	66.25	66.41	66.23	66.29	66.89	66.78
HR45N	14B6233	51.82	51.76	52.01	51.01	52.63	52.14
HR15N	14B4032	86.72	86.98	86.41	85.68	87.13	86.47
	14B5235	92.69	92.71	92.34	91.26	92.75	92.48

The uncertainties associated with the above values are as follows: the NPL hardness values have an uncertainty no worse than ±0.34 HRC, ±0.40 HR45N, and ±0.30 HR15N, while the Ellis Co. hardness uncertainty values are no worse than ±0.37 HRC, ±0.44 HR45N, and ±0.41 HR15N. Both NPL and Ellis Co. uncertainties are expanded uncertainties at a 95 % level of confidence.

ST11864 in the lower range of the HRC scale. This comparison becomes more obvious in Figs. 4 and 5. It can be seen that indenter ST11865 does not penetrate as deeply as ST11864 at higher forces, but indenter ST11865 penetrates more deeply at lower forces. This is why the ST11865 indenter reads lower on HR15N scale.

The physical geometries of the indenters are given in Table 1. It shows the radius of ST11865 to be smaller than ST11864. However, the angle is about the same. The smaller tip radius accounts for the lower hardness reading of indenter ST11865 at HR15N. The depth curves may give some information about the geometry of the indenter that the direct verification did not. In any case, Table 1 also supports the performance shown by indenters 1922 and 40222.

In 2004, indenters ST11864 and ST11865 were tested on a secondary hardness tester at Ellis Co. and in the primary hardness machine at NPL. The values are shown in Table 3.

On the secondary hardness tester at Ellis Co., the depth curve can be seen in Fig. 4. On the lower forces such as 90 HR15N, ST11865 reads lower than ST11864. The curve climbs higher and shows that ST11865 reads higher than ST11864 on 25 HRC.

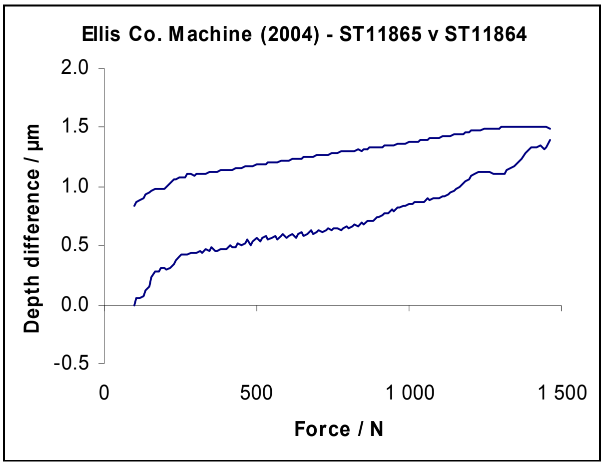

Fig. 4. Comparison of depth curves of indenter ST11865 vs. ST11864 on Ellis Co. tester in 2004

After testing indenters ST11864 and ST11865 on the secondary tester, they were again compared against each other on the tester at the NPL facility. Again, indenter ST11865 read lower on lower forces at high hardness and higher at high forces at lower hardness. This can be seen in Fig. 5. The smaller radius of 200 µm on indenter ST11865 is consistent with the lower performance on the HR15N scale test. While the angles of both indenters are about the same, indenter ST11865 reads higher at 25 HRC. It is possible that the depth curve indicates some characteristic that the usual geometry verification cannot determine. In any case, this curve is consistent with the one given by the secondary tester.

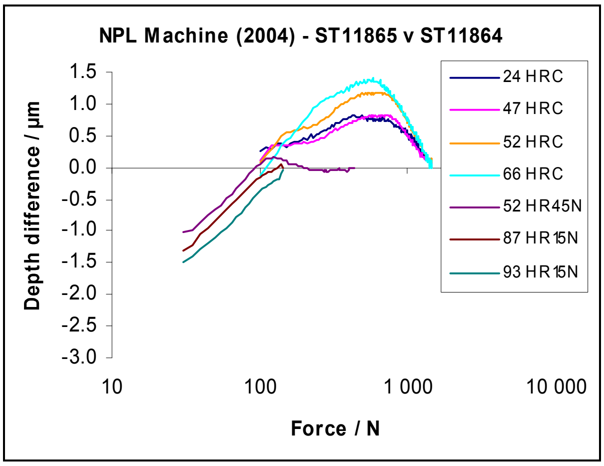

Fig. 5. Comparison of indenters ST11865 and ST11864 in NPL machine in 2004

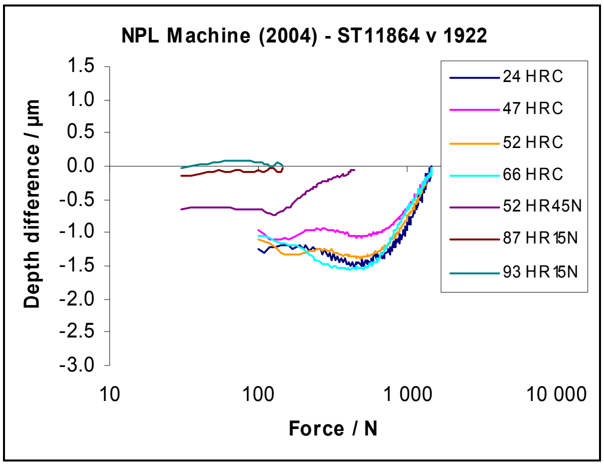

Fig. 6. Comparison of indenters ST11864 and 1922 in NPL machine in 2004

Comparisons with other indenters were also performed at the NPL facility. Two indenters, 1922 and 40222 were compared against ST11864, ST11865, and each other. Again, these values can be found in Table 3. When indenter ST11864 was compared against 1922, it was found that both tested about the same at HR15N but not as well at HRC. This can be seen in Fig. 6. While the radius values support the comparable HR15N values, the angles do not indicate comparable HRC values. It is possible that again the depth curves indicate something that the direct verification of geometry does not.

Better agreement with geometry can be seen when comparing indenters ST11864 and 40222. In this case, the larger radius of ST11864 has a higher depth curve at lower forces during the HR15N test. The smaller angle of ST11864 also tested lower at high forces and low HRC. This can be seen in Fig. 7.

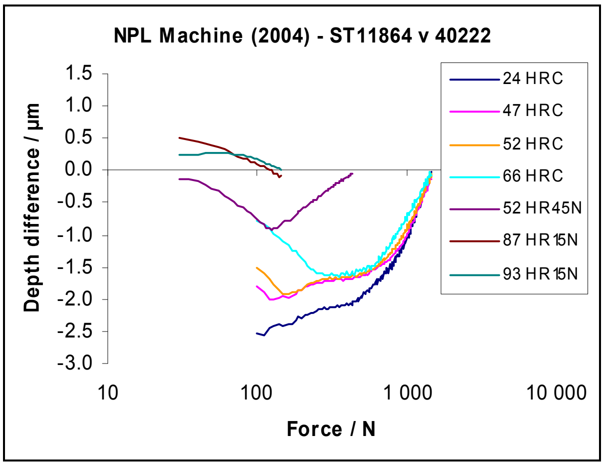

Fig. 7. Comparison of indenters ST11864 and 40222 in NPL machine in 2004

When comparing indenters ST11865 to 1922, the depth curves were lower for indenter ST11865. Although the geometry appeared to be about the same, the curves did not agree as shown in Fig. 8.

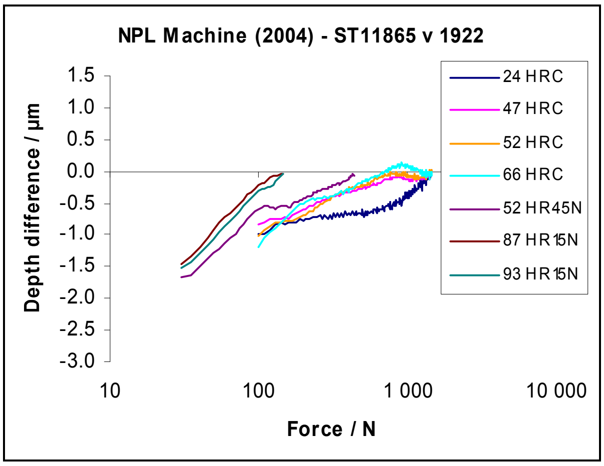

Fig. 8. Comparison of indenters ST11865 and 1922 in NPL machine in 2004

Better agreement can be seen in the comparison of indenter ST11865 and 40222 on the angle but not the tip radius. In this case the indenter ST11865 reads lower than 40222 at HR15N but has a larger radius. Indenter ST11865 reads lower than 40222 on HRC and is consistent with the geometry. These curves can be seen in Fig. 9.

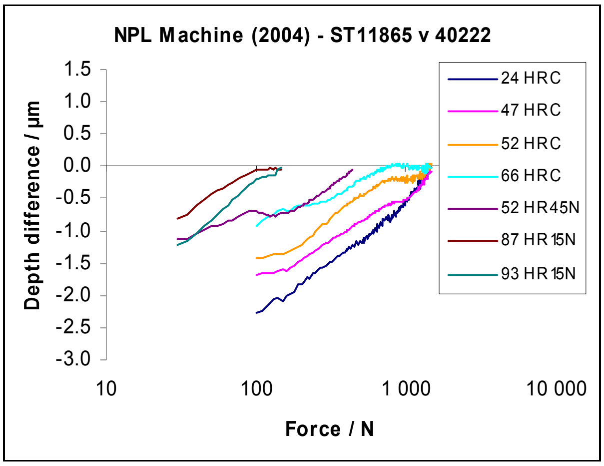

Fig. 9. Comparison of indenters ST11865 and 40222 in NPL machine in 2004

Finally, indenters 1922 and 40222 were compared against each other at NPL. This comparison agreed the best with the geometry. The larger radius of indenter 1922 read higher at HR15N and its smaller angle read lower at HRC. This can be seen in Fig. 10.

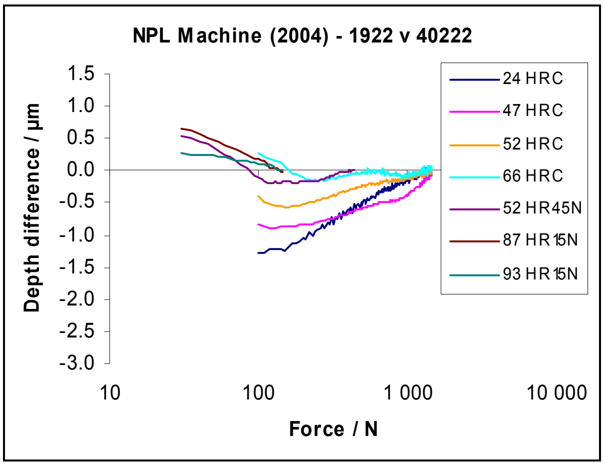

Fig. 10. Comparison of indenters 1922 and 40222 in NPL machine in 2004

When comparing indenters 1922 and 40222, it appears that a significant difference in geometry can accurately indicate the indenter performance. Indenters that have geometry that is similar can have different depth curves.

The following may be an explanation depth curves do not always agree with the indenter geometry determined during direct verification.

It is possible that the method used during the direct verification of the indenter geometry is not accurate enough to correctly measure the whole shape of the indenter. This may be the resolution of the measuring device or the fact that the whole surface of the indenter can not be measured that method. There may also be other characteristics of the indenter other than geometry that effect the depth and performance such as diamond finish and the mount.

The most likely approach to characterising indenters is verifying the indenter through direct verification of geometry. If the user's tolerance is fairly wide, it may be sufficient to accept only the fact that it has met the requirements of shape. For calibration purposes where greater indenter accuracy is needed, tighter geometry and performance criteria must be met. At the highest levels where two indenters appear to have the same geometry, the depth curves may assist in the selection.

4.2. Uses of the depth curves.

Depending on the ultimate use of the Rockwell indenter, the best indenter should be chosen appropriately. In the case of national laboratories and secondary laboratories, it is important to choose indenters that are as identical in performance as possible so that hardness measurements will be the same. The scales such as HR15N have been a problem since performance can be drastically different from one indenter to another. This can be particularly true even when two indenters read the same on the HRC scale but diverge in readings when used on HR15N. It is hoped that data from depth curves will help obtain these indenters since direct measurements for geometry has been a useful guide but still accepts indenters that may read significantly different on the same and other Rockwell scales.

5. CONCLUSIONS

Indenters contribute significant errors to hardness measurements. Since the current method of direct verification of indenter geometry can not absolutely predict the performance of the indenter, another method is needed. Further studies using depth measurement should be done to see if diamond indenters could be more accurately characterised.

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Author: Mr. Robert A. Ellis, David L. Ellis Company, Inc., Box 592, 310 Old High Street, Acton, MA, 01720, 978-897-1795 phone, 978-897-0844 fax, dlellisco@aol.com

Mr. Paul Mumford, United Testing Systems, Inc., 5802 Engineer Drive, Huntington Beach, CA 92649, 714-638-2322, mumford@tensiletest.com

Mr. Samuel Low, NIST, Inc., 100 Bureau Drive, Gaithersburg, MD 20899-8553, 301-975-5709 phone, samuel.low@nist.gov

Mr. Andy Knott, National Physical Laboratory, Queens Road, Teddington, Middlesex, United Kingdom, TW11 0LW, tel +44 20 8943 6180, andy.knott@npl.co.uk