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DETERMINATION OF SENSITIVITY COEFFICIENTS FOR ROCKWELL HARDNESS SCALES HR15N, HR30N, AND HRA

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Abstract: This report describes the work carried out to provide sensitivity coefficients for the Rockwell HRA and Superficial Rockwell HR15N and HR30N scales. Sensitivity coefficients were determined for the preliminary test force, total test force, force duration times, loading times, and loading rates.

Work was carried out at both the National Physical Laboratory (NPL) in Teddington, UK and the National Institute of Standards and Technology (NIST) in Gaithersburg, USA.

Keywords: hardness, sensitivity coefficients, uncertainty

1. INTRODUCTION

The determination of a hardness value depends on the results of measurements of a large number of different parameters, such as force, diameter, depth, time, radius, and angle. Each of these measurements has an associated uncertainty, and each of these uncertainties will contribute to the overall uncertainty of the hardness value.

The relationship between the uncertainty associated with the parameter and the uncertainty associated with the resultant hardness value is given by a sensitivity coefficient c_i defined as the change in hardness H resulting from a change in the input parameter x_i:

$$c_i = \frac{\Delta H}{\Delta x_i} \quad (1)$$

Sensitivity coefficients can also be used to make corrections to hardness values in situations in which the measured value of an input parameter differs from the value specified within the relevant Standard or, where a range of values is permitted within the Standard, to correct the hardness to a nominal input parameter value.

Some sensitivity coefficients can be calculated by taking partial derivatives of the equation defining the hardness value. Many sensitivity coefficients, however, can only be determined by practical experiment – this is done by varying the parameter of interest, while keeping all other inputs as constant as possible, and determining the effect on the measured hardness. Sensitivity coefficients determined by such practical work are generally only applicable to the particular material of the reference block.

2. EQUIPMENT

The NPL test work was performed in a 1.5 kN hardness standard machine (Fig. 1). Which uses a servo-controlled screw drive to apply forces via a high accuracy load cell, traceable to NPL force standards. Indentation depth measurement is by a laser interferometer system, traceable to the UK realisation of the metre at NPL.

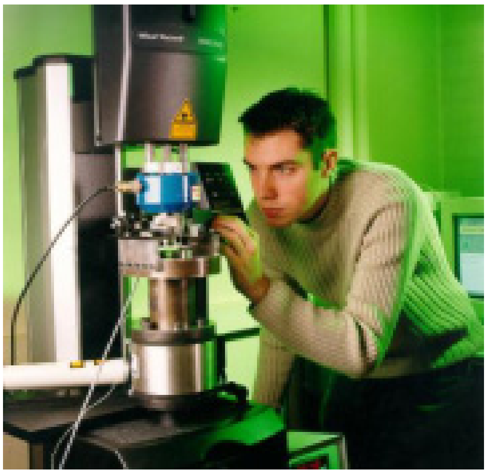

Fig. 1. NPL 1.5 kN hardness machine

The machine is PC-controlled and uses generalised waveforms, under closed loop control, to run standard indentation profiles. These profiles can be adjusted easily to model the variations in parameters required to give the different sensitivity coefficients.

The software used to control the machine streams data from all input channels - depth, force, time etc. - at a sample rate selected by the user throughout the hardness tests. This data is stored as a text-based file.

Further sensitivity coefficient determinations were made at NIST, using their primary Rockwell hardness standardising machine. The required forces are attained by means of dead-weight masses applied directly to the indenter support frame. The operation of the machine is under computer control, allowing wide variability in test parameters, and the acquisition of load, depth, and time data.

3. WORK

3.1. Parameters

ISO 6508-1 [1] specifies that the "duration of the preliminary test force F_0 shall not exceed 3 s" [preliminary test force duration, t_0], that the force shall be increased "from F_0 to F in not less than 1 s and not more than 8 s" [application time, t_{apply}], that the "total test force F shall be maintained for a duration of 4 s ± 2 s" [total test force duration, t], and that the final reading shall be made at a force of F_0 "after a short time stabilisation". ISO 6508-3 [2] specifies that "the final reading shall be made no less than 3 s nor greater than 5 s after removing the additional test force F_1" [final reading stabilisation time, t_{post}]. It also specifies that "During the final stage of the indentation process (approximately the range of 0.6 F to 0.8 F) the indentation speed should be in the range of 0.02 mm/s to 0.04 mm/s" [loading rate, v].

Bearing this in mind, Table 1 specifies the parameters and ranges selected for the tests performed at NPL.

Table 1. Parameters

Parameter	Value 1	Value 2	Value 3	Value 4
Preliminary test force duration, t_0	1s	2s	3s	N/A
Application time, t_{apply}	1s	3s	5s	8s
Total test force duration, t	2s	4s	6s	N/A
Final reading stabilisation time, t_{post}	3s	4s	5s	N/A
Loading rate [$\mu m \cdot s^{-1}$], v	10	20	30	40

The tolerance on the applied force is defined in ISO 6508-2 [3] as ±2 % for the preliminary test force and ±1 % for the total test force. Bearing this in mind, Table 2 specifies the values used for the sensitivity to force variation work at NPL.

Table 2. Force parameters

Parameter	% Change in force				
	Run 1	Run 2	Run 3	Run 4	Run 5
Preliminary test force, F_0	0	- 2	+ 2	0	0
Total test force, F	0	0	0	-1	+1

The NIST tests covered the HR30N and HR15N scales but not the application time parameter t_{apply} of the tests. The variations of the parameters studied at NIST were broader than at NPL giving an idea of their effect outside the tolerances of the ISO standards. Comparative work for the HRA scale was based on results previously obtained by NIST [4].

3.2. Method

For the tests carried out at NPL, five hardness tests were carried out on each block, for each parameter value, and the mean reading was obtained. Four blocks of different nominal hardnesses (Table 3) were used for each scale.

Each block was etched with a grid to allow identification of each indentation location. To minimise the effect of the hardness non-uniformity of the block, the locations of the five indentations were repeated as closely as possible in subsequent runs.

The work at NIST covered a greater range of values for the different parameters. Four hardness tests were carried out for each parameter value on blocks of three hardness levels (Table 3). When the NIST results and NPL results were compared the sensitivity coefficients were determined across the comparable range, although details of the different effects of the parameters outside of these limits are also described.

Table 3. Nominal hardness value of blocks used

Scale	Lab	Nominal hardness of blocks used			
HRA	NPL	83	73	65	59
HR30N	NPL	80	64	50	39
HR15N	NPL	92	83	75	68
HR30N	NIST	79	64	45	/
HR15N	NIST	91	83	72	/

4. RESULTS

At NPL, for each of the four hardness blocks in each scale, the mean measured hardness was plotted against the input parameter (preliminary or total test force, loading times and force duration times) and a linear least squares fit was applied to the data. The gradient of this line (the sensitivity of hardness to the input parameter) was plotted against hardness for the four blocks. Where applicable, the NIST results were also plotted on the same graphs.

Examples of these graphs are shown for each of the three scales investigated. The error bars relate to the linearity of the fit of hardness against input parameter at each of the hardness values – each error bar is ±2 times the standard error associated with the estimate of the gradient (sensitivity coefficient). The lines for the HRA scale force graphs represent results previously obtained by NIST [4].

In this paper, the uncertainty in individual hardness measurements is not an issue because the focus is on the differences between values obtained due to varying the test parameters. However, an individual Rockwell hardness measurement value is estimated to have an expanded uncertainty no larger than ± 0.1 Rockwell units without incorporating biases due to the indenters used.

4.1. HRA:

Figures 2 and 3 show the effects of varying the preliminary force and total force, on the measured hardness. It can be seen that the NIST results (solid line) match the NPL results (points with error bars) very closely.

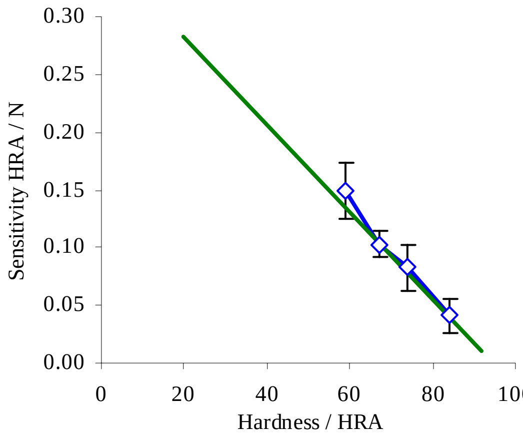

Fig. 2. HRA sensitivity to preliminary force variation

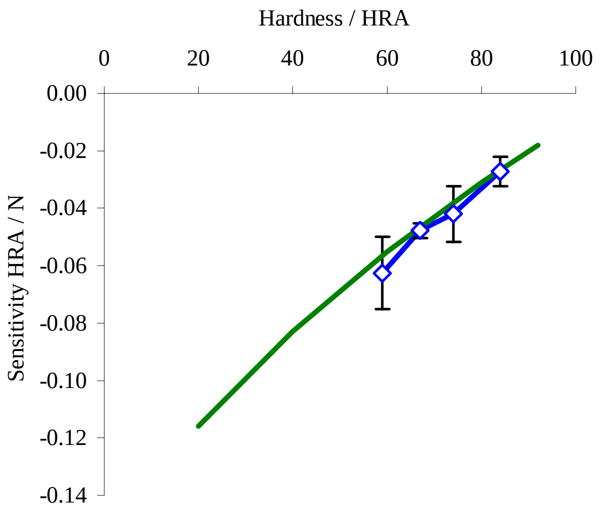

Fig. 3. HRA sensitivity to total test force variation

The effects of application time and final loading velocity on the measured hardness are shown in Figures 4 and 5. Obvious trends can be seen from the data. There is no comparison of these results with NIST results since NIST did not investigate the HRA scale for these parameters.

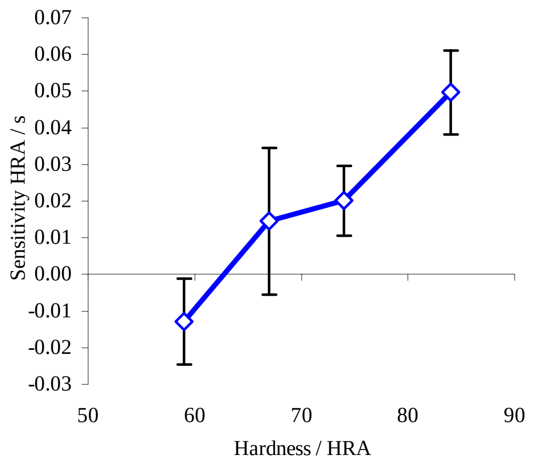

Fig. 4. HRA sensitivity to application time variation

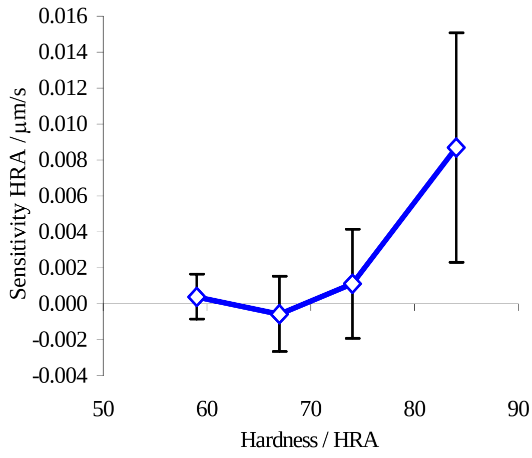

Fig. 5. HRA sensitivity indenter velocity variation

Sensitivity coefficients were calculated from the results of all the parameters. Table 4 lists these sensitivity coefficients for the HRA scale, based on the NPL results.

Table 4. NPL sensitivity coefficients for the HRA scale

		Hardness /HRA			
		59	67	74	84
		Sensitivity Coefficient HRA/Unit			
F_0	N	0.148	0.103	0.083	0.041
F	N	-0.063	-0.048	-0.042	-0.027
h	µm	-0.500	-0.500	-0.500	-0.500
t_0	s	0.132	0.016	0.009	-0.001
t_{apply}	s	-0.013	0.014	0.020	0.050
t	s	-0.061	-0.070	-0.036	-0.028
t_{post}	s	0.011	0.005	-0.015	0.007
v	µm/s	0.148	0.103	0.083	0.041

4.2. HR15N:

The effect of varying the velocity v of the final 25 % to 30 % of the main force application can be seen in Figure 6. The NPL results (points with error bars) were taken for the final 30 % while the NIST results (points connected with solid line) were for the final 25 %.

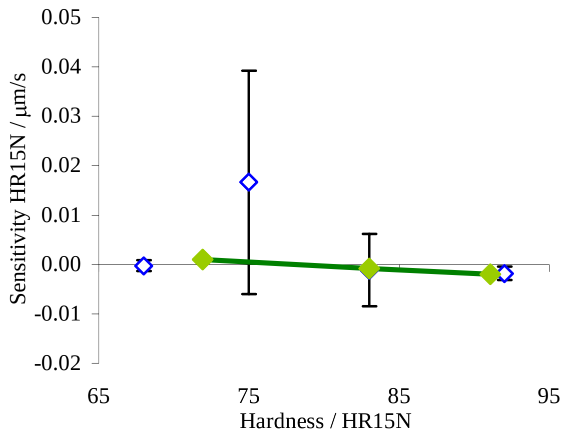

Fig. 6. HR15N sensitivity to indenter velocity variation

Where the two sets of data overlap similar trends can be seen. Although there is a shift in the NPL results for the 75 HR15N block, the uncertainty in the sensitivity coefficient covers the NIST results.

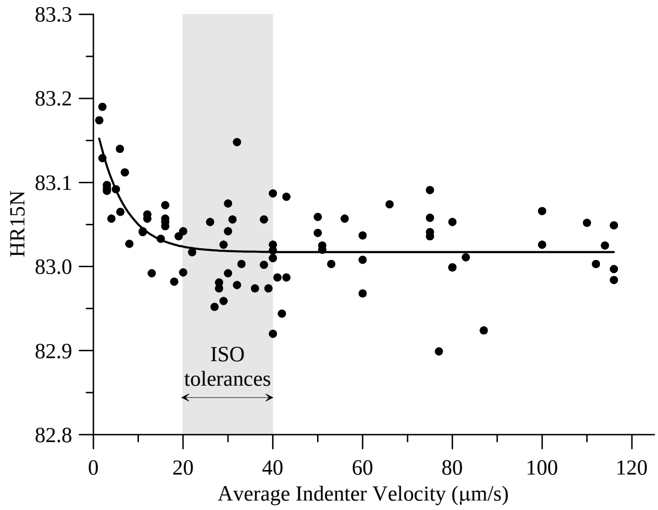

Fig. 7. Indenter velocity effect, NIST

Figure 7 shows the NIST data for the mid range hardness block. The wider range of velocities tested can be seen. The results match the other NIST results showing the hardness values to be stable after 20 µm/s, and also with minimal difference down to 10 µm/s. Below 10 µm/s there is a significant increase in the hardness value as the indenter velocity decreases. This underlines the importance of keeping the indenter velocity above 10 µm/s during the hardness test.

The effect of total test force duration on the block hardness is shown in Figure 8. The NPL (data points with error bars) and NIST (points connected with solid line) results again show good correlation.

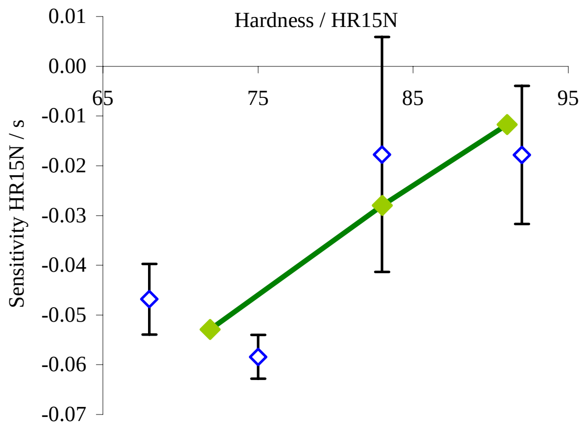

Fig. 8. HR15N sensitivity to total test force duration

Figure 9 shows an example of the NIST results for a 72 HR15N hardness block, demonstrating the effects of total test force duration time on the hardness. The curve fit is a fit to the indenter creep during these force duration times (converted to HR15N numbers) which NIST have always found to show good correlation for the HRB and HRC scales. The large data points are the average of 4 measurements and the error bars are the spread of the 4 data measurements. The gradient of the NIST graph for this and the gradients of the other hardness block graphs, were taken at matching force duration times to NPL and the standard range. These results were plotted, Figure 8, with the NPL results.

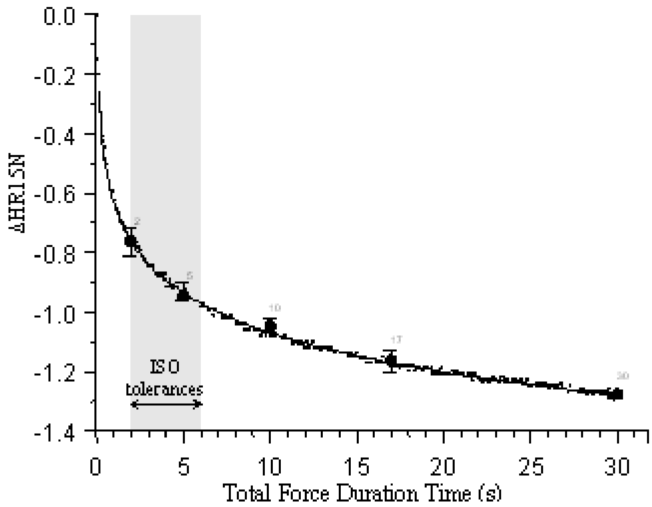

Fig. 9. 72 HR15N, Total Force Duration Time Effect, NIST

Sensitivity coefficients were calculated from the results of all the parameters. Table 5 lists the sensitivity coefficients for the HR15N scale, based on the NPL results, Table 6 shows the sensitivity coefficients based on the NIST results.

Table 5. NPL sensitivity coefficients for the HR15N scale

		Hardness /HR15N			
		68	75	83	92
		Sensitivity Coefficient			
		HR15N/Unit			
F_0	N	0.314	0.260	0.154	0.105
F	N	-0.269	-0.186	-0.145	-0.061
h	µm	-0.500	-0.500	-0.500	-0.500
t_0	s	0.171	0.146	0.012	0.080
t_{apply}	s	-0.014	0.006	0.019	0.016
t	s	-0.047	-0.058	-0.018	-0.018
t_{post}	s	0.037	0.073	0.058	0.043
v	µm/s	0.000	0.017	-0.001	-0.002

Table 6. NIST sensitivity coefficients for the HR15N scale

			Hardness /HR15N		
			72	83	91
			Sensitivity Coefficient		
		Range	HR15N/Unit		
t_0	s	1 s to 3 s	0.040	0.013	0.006
t	s	2 s to 6 s	-0.080	-0.053	-0.028
t_{post}	s	3 s to 5 s	0.001	0.001	0.002
v	µm/s	Final 25%	0.001	-0.001	-0.002

4.3. HR30N:

Results were again compared between NIST (without error bars) and NPL (with error bars) for the different parameters.

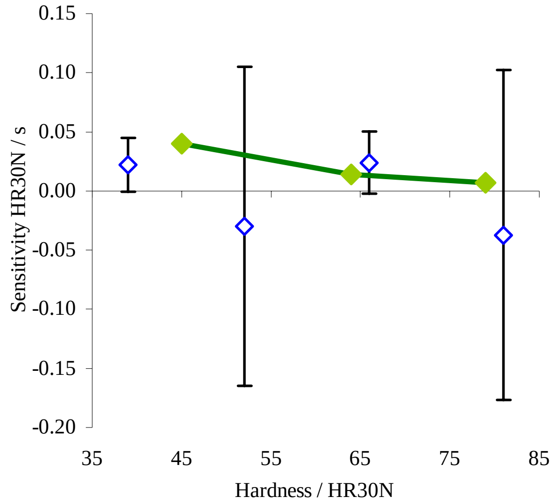

Fig. 10. HR30N sensitivity to preliminary test force duration

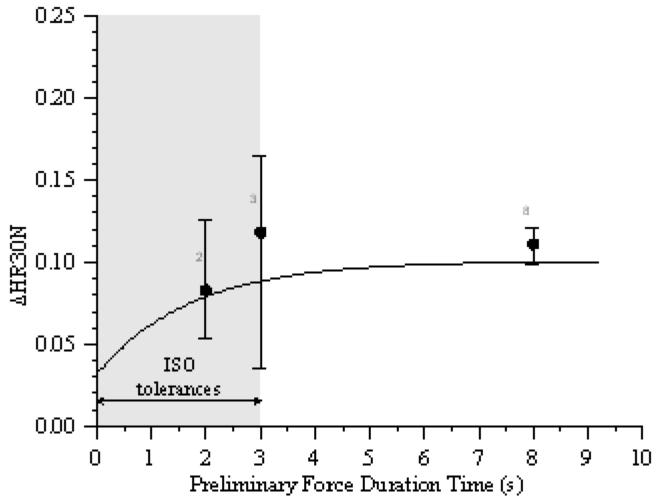

Fig. 11. 79 HR30N, preliminary test force effect, NIST

As can be seen from Figures 10 and 11, any dependency of the force duration times at the preliminary test force and final test force may be lost in the block's non-uniformity of hardness. The NPL results too are masked by the non-uniformity of the block.

Similar problems were encountered with the preliminary force and final forces on the HR15N scale, although coefficients have still been obtained for the range, based on the NPL results.

Sensitivity coefficients were calculated from the results of all the parameters. Table 7 lists the sensitivity coefficients for the HR30N scale, based on the NPL results, Table 8 shows the sensitivity coefficients based on the NIST results.

Table 7. NPL sensitivity coefficients for the HR30N scale

		Hardness /HR30N			
		39	52	66	81
		Sensitivity Coefficient HR30N/Unit			
F_0	N	0.389	0.185	0.206	0.174
F	N	-0.151	-0.137	-0.093	-0.077
h	µm	-0.500	-0.500	-0.500	-0.500
t_0	s	0.022	-0.030	0.024	-0.037
t_{apply}	s	-0.008	-0.005	0.008	0.048
t	s	-0.131	-0.114	-0.042	-0.077
t_{post}	s	0.027	-0.046	-0.083	0.050
v	µm/s	-0.014	0.007	0.014	-0.001

Table 8. NIST sensitivity coefficients for the HR30N scale

			Hardness /HR30N		
			45	64	79
			Sensitivity Coefficient		
		Range	HR30N/Unit		
t_0	s	1 s to 3 s	0.040	0.013	0.006
t	s	2 s to 6 s	-0.080	-0.053	-0.028
t_{post}	s	3 s to 5 s	0.004	0.004	0.005
v	µm/s	Final 25%	0.0004	-0.003	-0.008

Full details of the results for all the different parameters investigated by both NPL and NIST, across all three scales, can be viewed on the NPL website [5].

5. CONCLUSION

Varying the different parameters, even within the limits set out in the ISO standards [1, 2 and 3], can significantly affect the measured value of hardness.

The sensitivity coefficient work at NIST largely agrees with the data from NPL, giving greater confidence in the sensitivity coefficients obtained. For the superficial scales, the two sets of data from NIST and NPL, for the minor force duration times, t_{apply} and t_{post}, do not agree as well as the other parameters. But it can also be seen that the nonuniformity of the hardness blocks can easily mask the effect of these parameters at the lower force scales, causing any effects to be lost, and probably being the main cause of the difference in NPL and NIST results. Hopefully through additional studies this area of the sensitivity coefficients can be improved.

The sensitivity coefficients obtained here can be used to make corrections to hardness values in situations in which the measured value of an input parameter differs from its nominal value.

ACKNOWLEDGEMENTS

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