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EVALUATION OF THE UNCERTAINTY DUE TO ABBE'S ERROR FOR PRIMARY ROCKWELL HARDNESS STANDARD SYSTEM

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Abstract – The Primary Rockwell Hardness Standard System was established in the Center for Measurement Standards since July 1996 till June 1997. During the time, a laser interferometer, HP10737R 3-axis compact interferometer system, was substituted for the optical linear scale and combined with the mechanical structure of the original system to measure the Rockwell Hardness nominated values from 20 HRC to 70 HRC[1,2,3,4].

Subsequently the laser interferometer was performed the measurement of the pitch and yaw of the indenter when the hardness was measured; then we evaluated the uncertainty caused by the Abbe's error, pitch and yaw. The results showed that the expanded uncertainty of the primary Rockwell hardness standard system due to the Abbe's error of the indenter was 0,046 HRC at the confidence level of 95 %. The expanded uncertainty caused by the angle difference between the indenter moving axis and the measuring optical path was 0,0028 HRC at the confidence level of 95 %.

Keywords: Rockwell hardness, 3-axis compact interferometer, diamond indenter

1. INTRODUCTION

The Rockwell hardness number is calculated from the difference in the penetration depths before and after application of the total force, while maintaining the preliminary test force. For scales that use a spheroconical diamond indenter, the Rockwell hardness number is determined by [5,6]:

$$HRC = K_1 - (h_1 - h_0)/K_2 \tag{1}$$

where
HRC: Rockwell hardness unit;
h_0: penetration depth of preloading in mm;
h_1: penetration depth of total loading in mm;
K_1 = 100 mm: for diamond cone indenter;
K_2 = 0,002 mm: for Rockwell hardness.

The depths h_0 and h_1 are determined by the average of the optical paths X_1, X_2 and X_3 measured by the 3-axis compact interferometer. The measurement principle can be shown in Fig. 1.

The pitch and yaw of the indenter are calculated by X_1, X_2, X_3, L and d:

$$Pitch = \vartheta_y = \frac{(X_2 + X_3)/2 - X_1}{d} \tag{2}$$

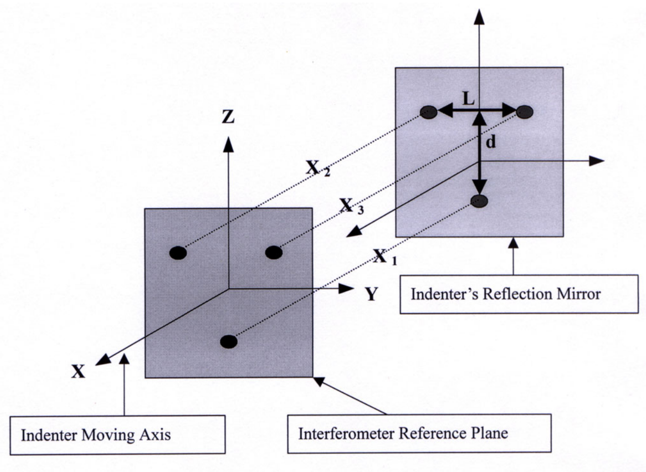

Fig. 1. The optical paths of 3-axis compact interferometer

$$Yaw = \vartheta_x = \frac{X_2 - X_3}{L} \tag{3}$$

where L and d are equal to 14,38 mm [2].

The standard uncertainty of the hardness measurement due to the Abbe's error, u_{Abbe}, can be determined by the sum of the yaw multiplied by its own Abbe's offset and the pitch multiplied by its own Abbe's offset, divided by K_2:

$$u_{Abbe} = \frac{|\Delta X_{Abbe}| + |\Delta Y_{Abbe}|}{K_2} \tag{4}$$

with

$$\Delta X_{Abbe} = Yaw \times \Delta X = \vartheta_x \times \Delta X \tag{5}$$

$$\Delta Y_{Abbe} = Pitch \times \Delta Y = \theta_y \times \Delta Y \tag{6}$$

where
ΔX_{Abbe}: Abbe's error in yaw-direction;
ΔY_{Abbe}: Abbe's error in pitch-direction;
ΔX : Abbe's offset in yaw-direction;
ΔY : Abbe's offset in pitch-direction.

2. EXPERIMENT

The primary Rockwell hardness standard system with the interferometer system was shown in Fig. 2. The interferometer system, which was calibrated, includes the laser head 3-axis compact interferometer and the optical receivers. The indenter, test block plate and the loading weights are below the interferometer system. The control system was in the right size that can control the loading time by dialling the panel switches. The value of the load can be controlled by a PC when the hardness was measured.

Fig. 2. Primary Rockwell Hardness Standard System in CMS.

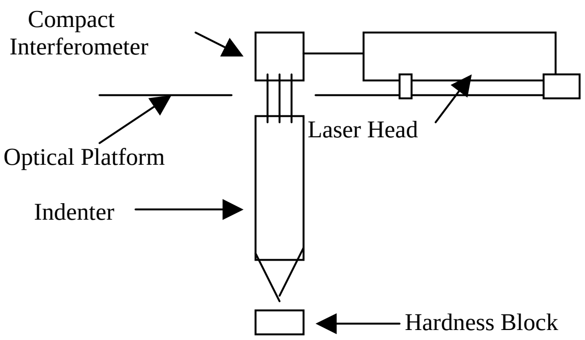

Fig. 3. Setup for the depth measurement

The corresponding optical path was shown in Fig. 3. The flatness of the optical table was measured by a flatness meter and the result caused an effect on the evaluation of cosine's uncertainty. We used the 3-axis compact interferometer to measure the depth and the pitch and yaw when the indenter was moving. The signals of the depth measurements were transferred to a PC by optical receivers and all of the data were calculated automatically. The three depths (X_1, X_2 and X_3), as shown in Fig. 1, were recorded during the hardness measurement. Substituting these values to (2) and (3) we can calculate the values of the pitch and yaw.

3. RESULTS

The pitch and yaw for individual HRA, HRB and HRC were measured during the hardness measurement. The typical results of the pitch and yaw are plotted in Fig. 4 and Fig. 5. In these figures, the diamond dots lines are the pitch and yaw of HRA, the square dots lines are the pitch and yaw of HRB and the triangle dots lines are the pitch and yaw of HRC.

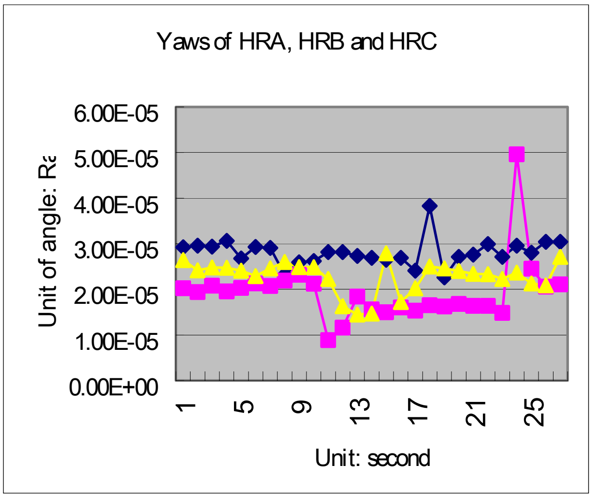

Fig. 4. Yaws of HRA, HRB and HRC.

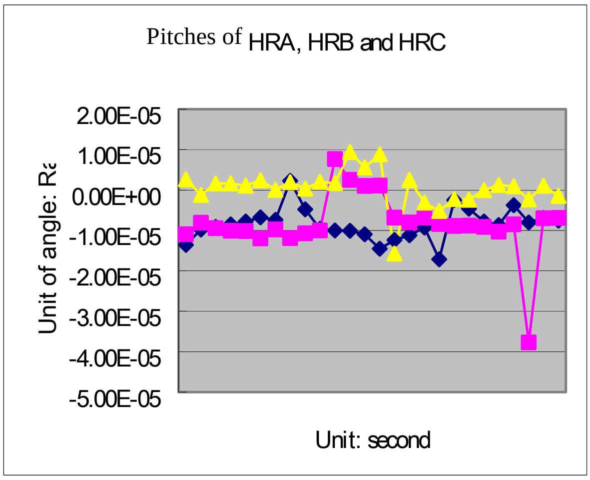

Fig. 5. Pitches of HRA, HRB and HRC

TABLE I. The results of the pitch and yaw for HRA

Nominal value	Count	Pitch	Yaw
HRA 87	1	-3,05E-5	4,91E-5
	2	9,70E-6	2,51E-5
	3	-1,39E-5	2,50E-5
	4	2,27E-5	2,58E-5
	5	5,55E-6	2,1E-5
	6	-7,4E-6	2,1E-5
HRA 76	1	-3,35E-5	4,32E-5
	2	-2,45E-5	2,87E-5
	3	-1,33E-5	2,35E-5
	4	-1,70E-5	3,83E-5
	5	-8,0E-6	3,41E-5
	6	-1,92E-5	3,13E-5
Max. value		-3,05E-5	4,91E-5

TABLE II. The results of the pitch and yaw for HRB

Nominal value	Count	Pitch	Yaw
HRB 90	1	3,93E-5	3,42E-5
	2	3,50E-5	1,75E-5
	3	4,39E-5	2,00E-5
	4	3,66E-5	1,93E-5
	5	5,07E-5	2,22E-5
Max. value		5,07E-5	3,42E-5

TABLE III. The results of the pitch and yaw for HRC

Nominal value	Count	Pitch	Yaw
HRC 65	1	-1,06E-5	2,54E-5
	2	-2,34E-5	3,72E-5
	3	2,67E-5	4,86E-5
	4	-4,26E-5	4,30E-5
	5	-4,26E-6	4,72E-5
HRC 46	1	-2,13E-6	3,80E-5
	2	4,50E-5	3,15E-5
	3	2,05E-5	3,63E-5
	4	-4,91E-5	3,65E-5
	5	-1,70E-5	3,83E-5
	6	1,80E-5	5,02E-5
HRC 20	1	-2,11E-5	5,00E-5
	2	-1,00E-5	3,33E-5
	3	8,83E-6	3,03E-5
	4	2,08E-5	3,36E-5
	5	-2,67E-5	4,11E-5
	6	8,1E-6	3,86E-5
Max. value		-4,91E-5	5,02E-5

The data number of the pitch and yaw of the hardness measurement for HRA, HRB and HRC are twelve, five and seventeen respectively. The results of the pitch and yaw for the nominal values HRA 87 and HRA 76 are listed in TABLE I, and the maximum values of the pitch and yaw are -3.05×10^{-5} radian and 4.91×10^{-5} radian respectively. The results of the pitch and yaw for the nominal value HRB 90 are listed in TABLE II, and the maximum values of the pitch and yaw are 5.07×10^{-5} radian and 3.42×10^{-5} radian respectively. The results of the pitch and yaw for the nominal values HRC 65, HRC 46 and HRC 20 are listed in TABLE III, and the maximum values of the pitch and yaw are -4.91×10^{-5} radian and 5.02×10^{-5} radian respectively. These maximum values of the pitch and yaw can be used to calculate the Abbe's error, and the measured data of the Abbe's offset in pitch and yaw directions are as shown in Table IV. Then the uncertainties can be determined for the related HRA, HRB and HRC units as follows:

A. The standard uncertainty due to Abbe's error of the hardness measurement for HRA:

$$(Pitch_{Max})_{HRA} = -3.05\times10^{-5};\ (Yaw_{Max})_{HRA} = 4.91\times10^{-5}$$

$$\Delta X_{Max} = 0.6 \text{ mm};\ \Delta Y_{Max} = 0.3 \text{ mm}$$

$$(u_{Abbe})_{HRA} = \frac{\Delta X_{Abbe} + \Delta Y_{Abbe}}{K_2} = \frac{\left|(Yaw_{Max})_{HRA}\times\Delta X_{Max}\right| + \left|(Pitch_{Max})_{HRA}\times\Delta Y_{Max}\right|}{K_2} = 0.020 \text{ HRA}$$

where

$(Pitch_{Max})_{HRA}$: the maximum value of the pitch for HRA;

$(Yaw_{Max})_{HRA}$: the maximum value of the yaw for HRA;

ΔX_{Max} : the maximum value of the Abbe's offset in yaw-direction;

ΔY_{Max} : the maximum value of the Abbe's offset in pitch-direction;

$(u_{Abbe})_{HRA}$: standard uncertainty caused by the Abbe's error for HRA.

B. The standard uncertainty due to Abbe's error of the hardness measurement for HRB:

$$(Pitch_{Max})_{HRB} = 5.07\times10^{-5};\ (Yaw_{Max})_{HRB} = 3.42\times10^{-5}$$

$$\Delta X_{Max} = 0.6 \text{ mm};\ \Delta Y_{Max} = 0.3 \text{ mm}$$

$$(u_{Abbe})_{HRB} = \frac{\Delta X_{Abbe} + \Delta Y_{Abbe}}{K_2} = \frac{\left|(Yaw_{Max})_{HRB}\times\Delta X_{Max}\right| + \left|(Pitch_{Max})_{HRB}\times\Delta Y_{Max}\right|}{K_2} = 0.018 \text{ HRA}$$

where

$(Pitch_{Max})_{HRB}$: the maximum value of the pitch for HRB;

$(Yaw_{Max})_{HRB}$: the maximum value of the yaw for HRB;

$(u_{Abbe})_{HRB}$: standard uncertainty caused by the Abbe's error for HRB.

C. The standard uncertainty due to Abbe's error of the hardness measurement for HRC:

$$(Pitch_{Max})_{HRC} = 4.91\times10^{-5};\ (Yaw_{Max})_{HRC} = 5.02\times10^{-5}$$

$$\Delta X_{Max} = 0.6 \text{ mm};\ \Delta Y_{Max} = 0.3 \text{ mm}$$

$$(u_{Abbe})_{HRC} = \frac{\Delta X_{Abbe} + \Delta Y_{Abbe}}{K_2} = \frac{\left|(Yaw_{Max})_{HRC}\times\Delta X_{Max}\right| + \left|(Pitch_{Max})_{HRC}\times\Delta Y_{Max}\right|}{K_2} = 0.023 \text{ HRC}$$

where

$(Pitch_{Max})_{HRC}$: the maximum value of the pitch for HRC;

$(Yaw_{Max})_{HRC}$: the maximum value of the yaw for HRC;

$(u_{Abbe})_{HRC}$: standard uncertainty caused by the Abbe's error for HRA.

TABLE IV. Abbe's offset in pitch and yaw directions (unit: mm)

Count	Abbe's offset in pitch-direction	Abbe's offset in yaw-direction
1	0,2	0,6
2	-0,1	0,2
3	0,1	0,3
4	0,1	0,3
5	0,0	0,3
6	0,3	0,3
7	0,0	0,6
8	0,2	0,4
9	0,3	0,5
10	0,3	0,4

D. The standard uncertainty caused by the optical path:

This uncertainty was caused by the angle difference between the indenter moving axis and the measuring optical path. The perpendicularity of the indenter was within $90^o\pm0{,}1^o$[1]. On the optical plate the flatness of twenty locations were measured, as shown in Table V, to determine the flatness of the optical table.

Since the flatness of the compact interferometer was measured under $0{,}1^o$, the optical paths in the compact interferometer were assumed parallel. Thus the angle between the indenter moving axis and the measuring optical path was less than $0{,}3^o$. The caused standard uncertainty of the hardness measurement, u_{COS}, can be determined by:

$$u_{COS} = \frac{\Delta h(1-\cos 0.3^o)}{0.002} = 0.0014 \text{ HR}$$

where $\Delta h \le 0.2$ mm.

4. CONCLUSIONS

For the hardness measurement system in the Center for Measurement Standards, it's very difficult to determine the uncertainty of the hardness measurement due to the Abbe's error when the original optical grating measurement system was used. The optical grating measurement system is not an intrinsic Abbe's error measured system, since the optical grating system is compact and parallel to the axial direction of the indenter, the pitch and yaw can't be measured easily at the same time while the hardness is measured. Using the 3-axis compact interferometer system, we got an easy method to evaluate the uncertainty of the hardness measurement due to the Abbe’s error. The corresponding expanded uncertainties are 0,040 HRA, 0,036 HRB and 0,046 HRC at the confidence level of 95 %. The expanded uncertainty caused by the angle difference between the indenter moving axis and the measuring optical path was 0,0028 HRC at the confidence level of 95 %. After this evaluation, we got more complete information of the primary Rockwell hardness standard system.

TABLE V. The flatness of the optical table

Location count	East-West	Location count	South-North
1	0,1^{o}	11	0,2^{o}
2	0,1^{o}	12	0,2^{o}
3	0,2^{o}	13	0,2^{o}
4	0,1^{o}	14	0,2^{o}
5	0,2^{o}	15	0,2^{o}
6	0,2^{o}	16	0,2^{o}
7	0,2^{o}	17	0,2^{o}
8	0,2^{o}	18	0,2^{o}
9	0,1^{o}	19	0,2^{o}
10	0,1^{o}	20	0,2^{o}

REFERENCES

[1] Chiu-Hsin Chen, Fu-Lung Pan and Sheau-shi Pan, "The evaluation of Rockwell hardness primary standard system", *Center for Measurement Standards*, Technical Report, No. 07-3-87-0002, 2001.

[2] HEWLETT PACKARD, “Choose from a Large Selection of Optical Components for System Design Flexibility”, 2001.

[3] Chiu-Hsien Chen, Sheau-shi Pan, Chi-Sheng Chang, Chin-Fen Duann, Jia-Ruey Duann, Fu-Lung Pan and Chih-Hung Yang, “High Precision Evaluated in the Rockwell Hardness Primary Standard System”, *Proceedings of International Symposium on Advances in Hardness Measurement*, pp. 80-84, September 1998, Beijing, China.

[4] ASTM E18-94, "Standard test methods for Rockwell hardness and Rockwell superficial hardness of metallic materials", *ASTM*, Philadelphia, PA, 1995.

[5] ISO 6508 -1, "Metallic materials – Rockwell hardness test – Part 1: Test method (scales A, B, C, D, E, F, G, H, K, N, T)", *ISO*, Geneva, 1999.

[6] J. - F. Song, S. Low, D. Pitchure, A. Germark, S. DeSogus, T Polzin, H. - Q. Yang, H. Ishida and G. Barbato, “Establishing a world-wide unified Rockwell hardness scale with metrological traceability”, *Metrologia*, vol. 34, pp. 331-342, 1997.

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