A method of measuring the arc radius of Rockwell diamond indenter

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Key words: Rockwell hardness, diamond indenter, radius recognition, simplicity algorithm, uncertainty

Abstract: Rockwell hardness is the most widely used hardness measurement method in industry at present. Taking superficial Rockwell primary standard machine in National Institute of Metrology(China) as an example, the uncertainty caused by the radius of the indenter arc accounts for 50% of the total uncertainty. In view of the important influence of the arc radius at the top of Rockwell diamond indenter on the evaluation of Rockwell hardness uncertainty, a profile projection system is established which is composed of lens, industrial camera and area-source of light. After pictures are obtained with camera, the next task for these pictures is to be calculated to get target parameter. The target parameter is obtained by profile extraction and radius calculation. In this paper, a new method is proposed as an algorithm criterion that sum of absolute value of data points and fitting arcs is used. Simplicity algorithm is introduced to iteratively solve the algorithm criterion. The purpose of using the algorithm is to eliminate the influence of outlier noise points. To verify the validity of the method in this paper, we conduct a series of experiments. The traceability experiment with standard sphere shows that the expanded uncertainty of the system of the instrument can achieve 1.0 µm, k=2. The uncertainty of measurement result with Rockwell diamond is 1.5 µm, k=2. The method in this paper bases on a simple-structural system, has high measurement accuracy, and can be used for rapid screening, evaluation, verification and calibration of Rockwell diamond indenters in industry.

1. Introduction
Rockwell hardness is the most widely used hardness measurements in industry.[¹] In the various factors that affects its uncertainty, the geometrical parameters of diamond indenter are the most critical impact factors. These factors are conical angle, axis inclination angle, arc radius and et al. Taking the HRN scale of the surface Rockwell hardness primary standard machine as an example, the uncertainty caused by the radius of the indenter arc accounts for 50% of the total uncertainty. The measurement of the arc radius becomes a problem to be studied and solved.[²⁻⁵] Diamond indenter is a transparent object with very small size. Rockwell indenter has a cone angle 120°, a length of generator 0.4mm, a arc radius of 200µm. And the generator is tangent to the arc. Currently, there are several arc measuring method such as curvature sample comparison method, contact probe scanning method⁶, confocal microscopy method⁷⁻⁸, LVDT displacement rotation measurement method, contour projection method⁹ and so on. For primary reference indenter, it requires a measurement method with high uncertainty level and tolerating high time-consuming. The radius measurement for common indenter should have the characteristics of low cost, fast convenient
and high uncertainty level.

2. System Composition and Structure

The optical part of the profile projection measurement system is composed of a surface light source, an imaging lens and an industrial camera, as shown in Fig. 1. The surface light source produces uniform projection light to the diamond indenter to be measured, and the parallel light carrying the profile information of the top of the indenter to be measured is incident to the imaging lens and collected by the industrial camera to the computer. In addition, the guide rail is designed on the imaging lens. The imaging lens is composed of two telecentric lenses. Its magnification is 4 x, working distance is 56 mm and depth of field is 0.1 mm. The feature of the lens is that both the image and the object are located at infinite distance. When the measured object moves up and down, the size of the object in the field of view will not change.

![Fig. 1 Structure of profile projection system](image)

3. Arc radius identification method

3.1 Profile extraction method.

The identification of the arc radius at the top of the indenter includes edge extraction and radius calculation. Here, Gauss function is to construct an image filter, the filter function is as follows:

$$G(x, y) = \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{(x^2+y^2)}{2\sigma^2}}. \tag{1}$$

In the equation, \(x, y\) is the row number and column number corresponding to the pixel, \(\sigma\) is the filter parameter. The picture \(f(x, y)\) is filtered smoothing to obtain \(f(x, y) \ast G(x, y)\). Computing the modulus \(M\) and direction \(\theta\) of the gradient vector of the picture

$$M(x, y) = \|f(x, y) \ast \nabla G(x, y)\|, \tag{2}$$

$$\theta(x, y) = \frac{f(x, y) \ast \nabla G(x, y)}{\|f(x, y) \ast \nabla G(x, y)\|}. \tag{3}$$

In order to locate the profile accurately, non-maximum suppression is needed to refine the profile band in gradient magnitude image \(M\). Interpolation is carried out along the gradient direction in the 3x3 neighborhood where the pixel point \((x, y)\) is the center. If the gradient magnitude \(M(x, y)\) at \((x, y)\) is larger than the gradient magnitude of the two adjacent points along the direction, the point will be recorded as candidate edge points, otherwise it will be recorded as non-profile image. Then we can get
candidate profile image \( N \).

The algorithm detects candidate profile points of candidate profile image \( N \) by setting high \( Th \) and low \( Tl \) thresholds through practical experience. The suspected edge points are further judged according to the connectivity of edges.

3.2 Radius calculation method.

According to the geometrical shape of ideal Rockwell hardness indenter prescribed by CCM-WGH and ISO, the tangent points \( P1 \) and \( P2 \) of arc and generator are located at \( \pm 100\mu m \) around the indenter axis on the horizontal direction. By constructing matching template to intercept the target window, a group of data points \((x_i, y_i)\) can be obtained. Using them to fitting the following formula:

\[
(x-x_c)^2 + (y-y_c)^2 = r^2. \tag{4}
\]

In the equation, \((x_c, y_c)\) is the center of the circle, \( R \) is the radius. The usual least squares algorithm requires the least square of the distance between the data point and the fitting arc. Thus in the following equation

\[
SS(x_i, y_i, r) = \sum_{i=1}^{n} \left[ r - \sqrt{(x_i-x_c)^2 + (y_i-y_c)^2} \right]^2, \tag{5}
\]

let \( SS(x_i, y_i, r) \) be the minimum. First of all, this formula can not be solved analytically. Secondly, the square term of the least square is very sensitive to outlier noise points. The algorithm is very effective when the data points fully conform to the normal distribution, but it is not so effective when in machine vision there are some points that deviate along a certain direction. Therefore, the absolute value of the sum of the distance between the data point and the fitting arc is chosen as the criterion. It is as follow

\[
SSA(x_i, y_i, r) = \sum_{i=1}^{n} \left| r - \sqrt{(x_i-x_c)^2 + (y_i-y_c)^2} \right|, \tag{6}
\]

Let \( SSA(x_i, y_i, r) \) be the minimum, we can get

\[
\nabla SSA(x_i, y_i, r) = \nabla \left[ \sum_{i=1}^{n} \left| r - \sqrt{(x_i-x_c)^2 + (y_i-y_c)^2} \right| \right] = 0. \tag{7}
\]

Formula (7) also has no analytic solution. Thus, we introduce Nelder-Mead algorithm, i.e. simplicity method, to solve the problem iteratively. A tetrahedron composed of four vertices is used to approximate the optimal point \( O(X, Y, R) \) step by step. Here, let \( O_1, O_2, O_3, O_4 \) be the vertex of a polyhedron, and satisfy \( SSA(O_1) \leq SSA(O_2) \leq SSA(O_3) \leq SSA(O_4) \). Fig.2 shows the flow chart of iteratively updating the tetrahedron to make it move and contract to approximate the optimal solution.
4. Experiment

4.1 Traceability method and experiment.

The uncertainty of arc radius measurement is evaluated by standard sphere. Take a standard sphere with the radius of 200.6 as an example, let’s analyze the uncertainty of the instrument. According to the calibration result of the standard sphere ball, the average deviation $\Delta R$ and the standard uncertainty $u(R_M)$ can be calculated, as shown in Table 1.

|  |  |  |  |  |  |
|---|---|---|---|---|---|
| Standard value $[\mu m]$ | Test values $[\mu m]$ | Average deviation $[\mu m]$ | $\Delta R[\mu m]$ | $u(R_M)[\mu m]$ |
| 200.6 | 200 | 200 | 200 | 200.5 | -0.1 |

The combined uncertainty of standard sphere measurement is calculated using the following equation:

$$u(R) = \sqrt{u^2(R_{RS}) + u^2(R') + u^2(R_M)}.$$ (8)

In the equation, $u(R_{RS})$ is measurement uncertainty from standard sphere calibration certificate, $k = 1$, $u(R')$ is the relative measurement uncertainty caused by instrument resolution, $u(R_M)$ is the standard uncertainty of radius measurement. The measurement uncertainty of sphere is $U(R_{RS}) = 0.8\mu m(k = 2)$, the effect of instrument resolution can be brought into repeatability, so it is neglected. From the information above, we can calculated the uncertainty of radius measurement, as shown in Table 2.
### Table 2: Uncertainty calculation of instrument radius measurement

| Quantity | Distribution Type | Standard Uncertainty $u(x_i)$ [$\mu m$] | Sensitivity Coefficient $c_i$ | Uncertainty $u_i(R)$ [$\mu m$] |
|----------|-------------------|----------------------------------------|-------------------------------|--------------------------------|
| $R_{RS}$ | normal            | 0.4                                    | 1                             | 0.4                            |
| $R'$     | rectangle         | 0                                      | 1                             | 0                              |
| $R_M$    | normal            | 0.2                                    | 1                             | 0.2                            |
| Combined standard uncertainty $u(R)$ |                             |                                         |                               | 0.5                            |
| Expanded uncertainty $U(R)(k = 2)$ |                             |                                         |                               | 1.0                            |

#### 4.2 Physical experiment.

Fig.3 and Table 3 show the contour projection and measurement result obtained from the experiment with standard Rockwell diamond indenters. The calculation of the results is:

\[
U_i(R_i) = 2 \times \sqrt{u_i^2(R_i) + u_i^2(R_i)} = 2 \times \sqrt{0.5^2 + [(202.54 - 197.77)/2.97]^2} / 9 = 1.5(\mu m).
\]

![Fig.3 The contour projection of Rockwell diamond indenter](image)

### Table 3: Radius measurement results of Rockwell diamond indenter

| Location angle [$^\circ$] | Test value of radius [$\mu m$] | The average |
|---------------------------|-------------------------------|-------------|
|                           | 1                             | 2          | 3          |                   |
| 0                         | 197.7                         | 197.77     | 198.64     | 198.06            |
| 5                         | 202.5                         | 202.52     | 202.41     | 202.49            |
| 90                        | 199.3                         | 198.68     | 198.65     | 198.88            |
| 135                       | 201.6                         | 200.91     | 200.50     | 201.01            |
| The average               | 200.1                         |             |             |                  |

#### 5. Concludes

This paper presents a method for identifying the arc radius of Rockwell diamond indenter, in which the absolute value of the sum of the distance and Nelder-Mead method are introduced. The traceability experiment with standard sphere shows that the expanded uncertainty of the system of the instrument can achieve 1.0 $\mu m$, $k = 2$. The uncertainty of measurement result with Rockwell diamond is 1.5 $\mu m$, $k = 2$. 

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The system has simple structure, fast identification process and high measurement uncertainty. It can be used for rapid screening, evaluation, verification and calibration of Rockwell diamond indenter in industry. In industry application, there are some interferences sources that affect the algorithm accuracy, which need to be investigated later. In summary, the method in this paper has strong robustness, high reliability and a worth of popularization.

6. References

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