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IMPROVED METHODS FOR ACCURATELY CALIBRATING THE 3D GEOMETRIES OF ROCKWELL INDENTERS

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Abstract − In this paper an improved method for calibrating the 3D geometry of Rockwell indenters using a metrological stylus profilometer is reported. The measured geometry of the indenter is not only applied to determine the quality of the indenter, but also used for correcting the hardness values for improved hardness measurement accuracy. A method for such a correction has been proposed. A virtual indentation device simulated using finite element method (FEM) has been developed. By applying both the measured and the theoretically ideal indenter geometries in the virtual device, two different hardness values HRC_{real} and HRC_{ideal} are obtained, respectively. The difference between HRC_{real} and HRC_{ideal} stands for the systematic deviation due to the indenter geometry and is used to correct the measured hardness values. Some experiments are carried out on the same group of 6 reference materials with a hardness ranging from 20 HRC to 65 HRC to verify our proposal. The geometries of three Rockwell indenters used are measured and further applied to correct the hardness values. By this correction technique the mean deviation between the three indenters on 6 reference materials could be reduced from 0.11 HRC to 0.03 HRC, indicating the effectiveness of the proposed method.

Keywords: Rockwell indentation, metrological stylus profilometer, correction

1. BASIC INFORMATION

The influence of the indenter geometry on the precision of hardness values is significant in all hardness test methods. This is especially true for Rockwell diamond indenters which have a relatively complicated geometry consisting of a ball cap bordering on a cone frustum. It is generally accepted that the geometry deviations of the Rockwell indenter deliver approximately 50% of the measurement uncertainty in its overall uncertainty budget of the Rockwell measuring method [1]. Although for the calibration of Rockwell indenters interferential and other optical methods with high resolution are widely used, a functional test of the Rockwell diamond indenters revealed that the uncertainty remains scarcely below approximately 0.3 HRC [2].

Therefore, it is a crucial task to measure the 3D geometries of Rockwell indenters accurately before applying them in hardness measurements. The obtained geometry not only offer the proof whether the quality of the indenter fulfills the corresponding criteria defined by the ISO standards, but also can be applied for correcting the measured hardness values for further improving the measurement accuracy.

In this study, we report an improved method to calibrate the 3D geometry of Rockwell indenters using a metrological stylus profilometer. In addition, finite element analysis (FEM) has been applied to correct the influence of deviation between real and ideal indenter geometry.

It is worth to mention that the presented method is also applicable to other types of indenters, although the results demonstrated in the paper are focused on Rockwell indenters.

2. MEASURE THE 3D GEOMETRY OF ROCKWELL INDENTERS

The 3D geometry of indenters is measured by means of a high precision stylus profilometer developed based on a nano measuring and positioning machine (NMM) [3-4]. Since the instrumentation, measurement strategy and data evaluation method used have been published elsewhere [5], we introduce them concisely for the completeness of the paper.

The principle of the instrument used is shown in Figure 1. The indenter of interest is mounted on a motion platform of the NMM. When the sensor head is mounted, the stylus tip is located at the intersection point of the three measurement beams of the x, y and z interferometers. In such a way, the Abbe measurement principle is satisfied. During measurements, the indenter is moved by the NMM along the x-, y- and z-axes and its surface is measured by a stylus probe (type RFHTB-50, Mahr GmbH). In the instrument the stylus probe acts as a zero detector, that is, the output of the stylus probe is kept as a constant value by using the servo controlling the z-motion of the NMM. Therefore the 3D coordinates of the diplacement represent the 3D geometry of the indenter. Due to the use of three interferometers the coordinates are traceable and accurately with a resolution of 0.08 nm.

A special measurement strategy referred to as radial scan technique has been developed to measure the indenter geometry. Using this technique, the indenter is scanned radially with traces over the indenter apex. The radial scan is implemented by moving the indenter in a coordinated manner along the x-and y- axes simultaneously. Therefore, it is not necessary that the indenter is rotated during the measurements. This technique has advantages of measuring the indenter with higher pixel density near its apex.

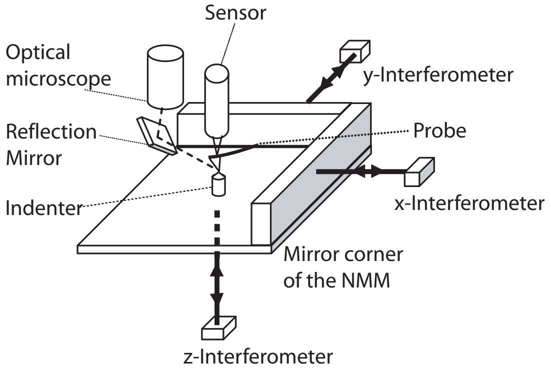


Fig. 1. Principle of the measurement device

Based on the measured 3D geometry of the Rockwell indenter, the area function, the ball cap radius and the cone angle of the indenter can be evaluated. The evaluation is carried out in the following steps:

- Erode [6] the measured 3D geometry to remove the dilation effect of the stylus tip,
- Extract the cone part from the measured 3D geometry and fit it by least squares method to a cone shape,
- Rotate the measured 3D geometry according to the fitted angles,
- Calculate the contour points of the indenter at a given indentation depth and fit the contour points by least squares method to a circle,
- Calculate the area function,
- Calculate the deviation of the obtained area function from that of an ideal indenter.

As an example, the measured 3D contour of a used Rockwell diamond indenter (No. 5977) is shown in Figure 2. The profile has a length of 520 µm and is measured at a speed of 10 µm/s. Each trace is recorded with 2000 pixels, yielding a pixel density of 260 nm/pixel. The area function of the measured Rockwell indenter is shown as the deviation between the real and ideal values in Figure 3. It can be seen that the deviation is positive at small indentation depths, indicating that the indenter is blunt which is probably caused by its hardness tests. This fact is confirmed by the fitted ball cap radius of 266.6 µm, which is much larger than its nominal value of 200 µm.

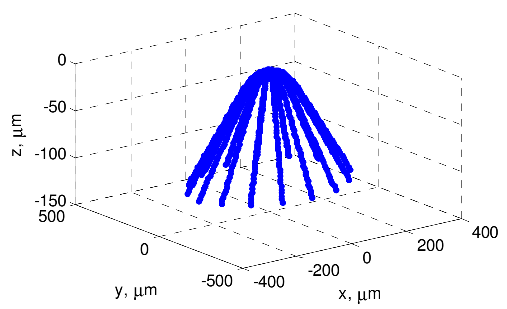


Fig. 2. Measured 3D contour of a Rockwell indenter

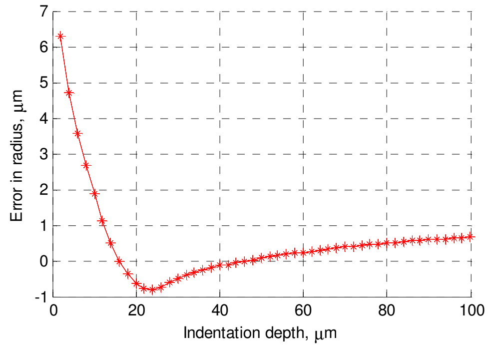


Fig. 3. The area function of the measured Rockwell indenter shown as the deviation between the real and ideal values.

3. CORRECTION OF HARDNESS USING FEM METHOD

Usually the measured 3D geometry of the Rockwell indenter is used solely for determining whether the quality of the indenter satisfies the ISO standards. In this study, an idea is proposed to correct the hardness values by compensating the influence of the indenter geometry, so that the hardness measurement accuracy can be enhanced. The basic idea of the proposed correction is straightforward, as shown in Figure 4. The core of the idea lies at a virtual indentation device simulated using the FEM software. By using the real measured and theoretically ideal indenter geometries in the virtual device, two different hardness values HRC_{real} and HRC_{ideal} are obtained, respectively. The difference between HRC_{real} and HRC_{ideal} stands for the error contribution from the indenter geometry, and therefore can be used to correct the measured hardness values HRC_m by:

$$HRC_c = HRC_m + C*(HRC_{ideal} - HRC_{real})$$

Where, HRC_c is the corrected hardness value and C is a scale factor which is set to be 1 in this study.

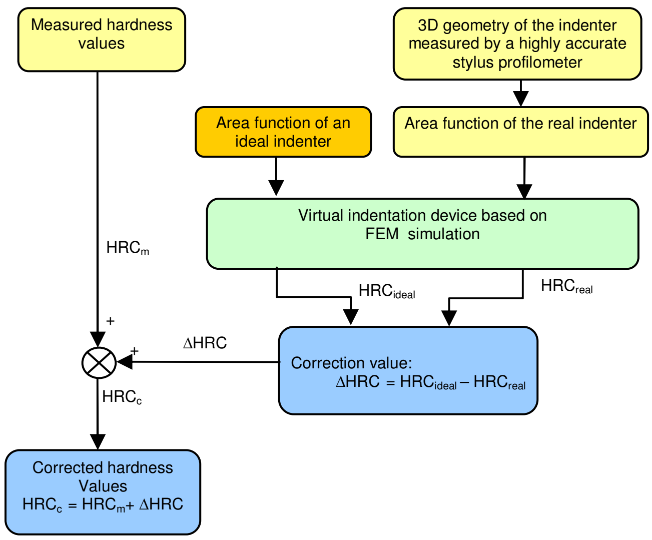


Fig. 4. Schematic diagram showing the proposed idea of correcting hardness values using FEM methods to compensate the influence of indenter geometry.

3.1. FEM model and meshing

The FEM simulation is performed using the Ansys® software version 12.1. As shown in Figure 5, a two dimensional (2D) FEA model is set up for the simulation since the Rockwell indenter is rotation symmetric. Compared to a 3D model, the 2D model needs much less computation time and storage capacity.

The reference materials used in our experimental study are selected to be the test material in simulation. The parameters of the material such as the Young's modulus and the yield stress are obtained from results of a tensile test.

The model is meshed with triangle-shaped elements. Two kinds of meshing strategies are tested. The first one is a uniform meshing strategy, where the contact area between the indenter and the sample is meshed with a same meshing size. The second one is a non-uniform meshing strategy, where the meshing size becomes gradually larger when the element is farer from the centre axis of the indenter.

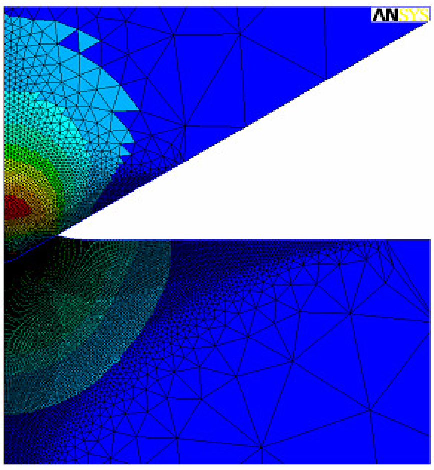


Fig. 5. The applied 2D FEM model meshed with non-uniform meshing strategy

In order to investigate which meshing strategy is better and to determine what is the optimum meshing size for obtaining satisfactory modelling and computation accuracy, simulations have been performed on the same test material using different meshing sizes and strategies. During the simulation, the indenter is loaded with a preliminary test force of 10 kilograms of force (kgf) and a total test force of 150 kgf, as defined in the standardised Rockwell test procedures of the HRC scale. The calculated force-displacement curves are shown in Figure 6. The curve is very smooth when the meshing size is fine (meshing size of 6 µm), however, its quality degrades if the meshing size increases due to the modelling and computation errors. In addition, it can be seen that the simulated force-displacement curve is very similar to the force-displacement curve measured in typical hardness tests.

In the FEM simulation process, the indentation depth h1 and h3 after the preliminary test load force is applied and the additional test force is unloaded are recorded, respectively. The Rockwell hardness value can then be calculated as:

$$HRC = 100 - (h3 - h1)/0.002$$

where, h1 and h3 are in millimetres.

Simulated results on the same test material using different meshing sizes and different meshing strategies are plotted in Figure 7. It can be seen that the deviation between two different meshing strategies may reach 3 HRC at a large meshing size of 35 µm; however, it is reduced down to 0.1 HRC when a finer meshing size of 7 µm is used. Based on this investigation result, we selected the non-uniform meshing strategy with a fine meshing size of 7 µm in our further study, since its computation time (about 30 minutes) is much less than that of the uniform meshing strategy.

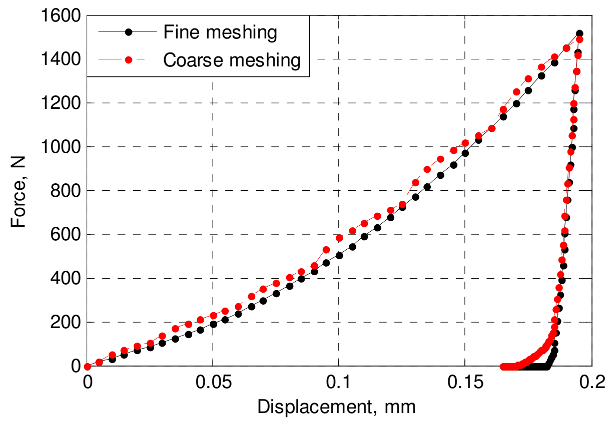


Fig. 6. The calculated force-displacement curve in simulations.

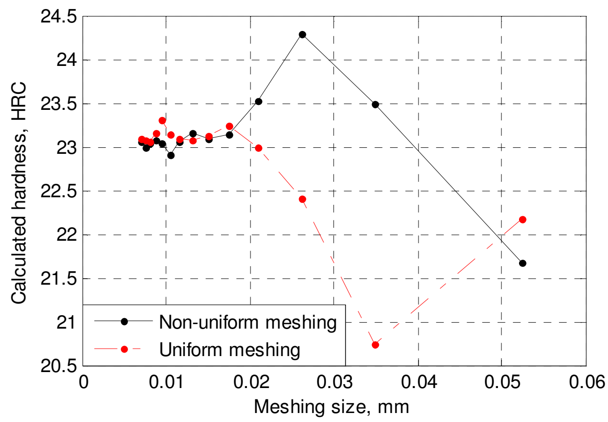


Fig. 7. The influence of the finite element meshing size on the calculation accuracy

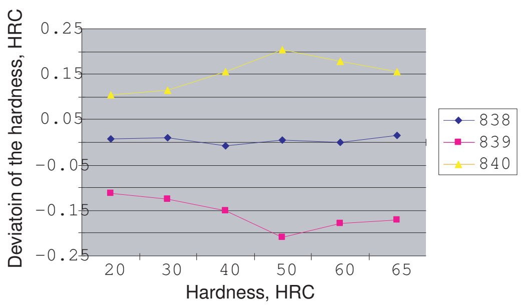
3.2. Results and discussions

In order to verify the proposed method, the geometries of three Rockwell indenters with serial number 838, 839 and 840 are determined using the developed method and their area functions are calculated. The indenters are then used to calibrate six reference materials with a hardness ranging from 20 HRC to 65 HRC. Ten repeated measurements have been performed on each reference material, and the mean value is calculated as the measured hardness for each reference material and each indenter. Ideally, the measured hardness values should be independent on indenters, that is, the results obtained by different indenters on the same reference material should be identical. However, we find discrepancies in the measured hardness values as shown in

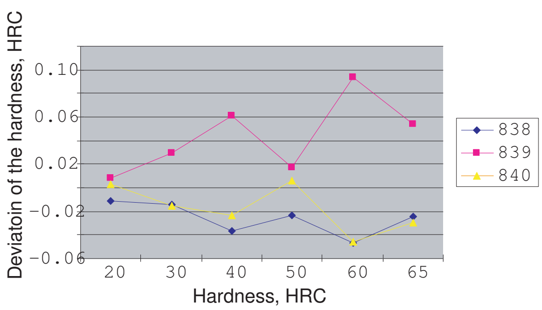
Figure 8(a). For instance, the hardness values measured by the indenter 840 on all reference materials are larger than that of the other two. The largest hardness discrepancy may reach more than 0.4 HRC. The mean value of measurement deviations is 0.11 HRC. Such a deviation can be attributed to the geometry deviation of the indenters.

We corrected the measured hardness values using the proposed correction method based on the FEM analysis method. The deviation from the corrected hardness values again is plotted in Figure 8(b). It clarifies that the discrepancies between the corrected results are reduced significantly. No clear offset appears anymore. The largest hardness discrepancy is reduced to 0.16 HRC. The mean value of measurement deviations is 0.03 HRC, about one fourth of the mean deviation of the uncorrected measurement results. This result indicates the effectiveness of our proposed correction method.

Furthermore, it can be seen that the agreement of the results of softer materials (small HRC values) is better than those of harder materials (large HRC values). The reason can be explained by their indentation process. When harder materials are tested under the preliminary test force only the ball cap part of the indenter penetrates into the material, while for softer materials the cone part of the indenter penetrates into the material. Since the ball cap of the indenter has a larger form deviation than its cone part as shown in Figure 8, it is understandable that it is more difficult to correct the hardness values of harder materials.



(a)



(b)

Fig. 8. Hardness deviations from the measured hardness value of three Rockwell diamond indenters obtained at six different hardness levels are shown in (a); and the deviations after applying the correction method are shown in (b).

4. EXISTING PROBLEM AND OUTLOOK

Although the proposed method works nicely in the given measurement example as shown in Figure 8, we found its correction performance was not so satisfying when it is applied for an indenter with a strongly worn ball cap. The problem was probably due to the fact that the meshing size at the apex region of indenter is still not fine enough, and consequently the FEM model does not well represent the worn ball cap of the indenter. To solve this problem, the FEM model and meshing strategy need to be further improved.

In addition, the three indenters used in the experimental study are relatively new and have good quality. In order to test whether the proposed method works well for all kinds of indenters at different quality levels, more investigations need to be carried out.

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