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PROGRESS IN THE CHARACTERIZATION OF THE GEOMETRY OF ROCKWELL DIAMOND INDENTERS

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Abstract − In this paper two methods for an improved characterization of the geometry of Rockwell diamond indenters are investigated: The establishment of a group standard of indenters and the derivation of an area function with a nano measuring machine. A group standard of indenters yields better statistical results than the calibration using only one indenter. Further, a group standard of indenters guarantees a higher stability of the Rockwell hardness scales in the case that an indenter is damaged and must be replaced by a new one. The second approach is based on the correction of the hardness test values using the indenter's area function determined by a high accuracy nano measuring machine. The investigation has proven that the range of the hardness deviations of a group of three Rockwell indenters amounting to ca. 0.4 HRC by the application of an area function with corrected hardness values can be further reduced to < 0.2 HRC for the lower hardnesses and to < 0.3 HRC for the higher hardnesses. The mean deviation of HRC values measured by this group of Rockwell indenters has been reduced from 0.11 HRC to 0.06 HRC by using the proposed correction method. In future correction methods for Rockwell diamond indenters usable for all standardized Rockwell hardness scales should be derived.

Keywords: Rockwell diamond indenter, group standard, indenter area function, stylus profilometer

1. INTRODUCTION

Rockwell tests are the most widely applied hardness tests in industry. Again, within the different standardized Rockwell hardness scales according to ISO 6508-1 [1], the scales which are realized with diamond indenters, like HRC, HRA and HRN, are of utmost importance for industrial practice.

As in most hardness test methods the influence of the indenter geometry on the precision of hardness values is significant. This is specially true for Rockwell diamond indenters which have a relatively complicated geometry consisting of a ball cap bordering on a cone frustum. Therefore the uncertainty of measurement of Rockwell hardness tests generally is determined by more than 50 % by the geometry deviations of the indenter.

Although for the calibration of Rockwell indenters interferential and other optical methods with high resolution are widely applied, the function test of the Rockwell diamond indenters reveals that the uncertainty remains scarcely under ca. 0.3 HRC.

Therefore the industry demands to develop indenter calibration methods with raised accuracy.

In this paper two approaches to the determination of the geometry of Rockwell diamond indenters have been investigated:

1) Establishment of a group standard
2) Determination of an indenter area function

The methods and the results of these two investigations will be reported. Finally both approaches will be compared with each other.

2. ESTABLISHMENT OF A GROUP STANDARD OF ROCKWELL DIAMOND INDENTERS

The idea of a group standard for Rockwell indenters has already theoretically been elaborated by R.S. Marriner [2] and F. Petik [3], but seldom applied so far. The indenters for the group standard were selected according to the following criteria:

- Fulfilment of the geometrical tolerances according to ISO 6508-3 [4]
- The mean value of the indenter deviations should be near the normative value
- The geometrical deviations of the indenters chosen for the group standard should be distributed symmetrically to the nominal value

In Table 1 the geometrical deviations of three Rockwell diamond indenters chosen for the group standard of the Rockwell hardness scale are drawn up.

Table 1. Geometrical deviations of Rockwell diamond indenters for the group standard

Indenter No.	Mean cone angle α	Mean radius R (mm)
838	120°01’	0.194
839	119°58’	0.195
840	120°02’	0.199
Mean value	120°00’20”	0.196

The mean values of the geometrical deviations in Table 1 allow the conclusion that the selection criteria for the group standard are fulfilled sufficiently, namely that the indenters fulfil the high quality requirements according to ISO 6508-3.

Fig. 1 shows the deviations of the three indenters listed in Table 1 from the mean hardness value of the three indenters which were obtained from hardness measurements on six different hardness reference blocks ranging from 20 HRC to 65 HRC. The mean hardness value on each hardness reference block was calculated from measurements on nine locations evenly distributed on the block. In this way the hardness inhomogeneity of the used hardness reference blocks can be neglected.

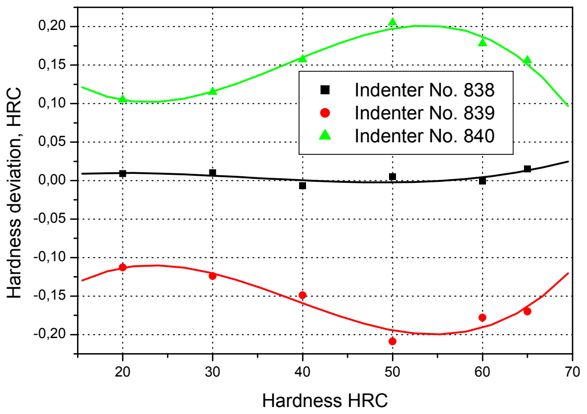

Fig. 1. Hardness deviations from the mean value of three Rockwell diamond indenters obtained for six different hardness levels.

3. DETERMINATION OF INDENTER AREA FUNCTIONS WITH A NANOMEASURING MACHINE

The area function for the description of the real geometry of hardness indenters is usually defined as the size of the indenter's projected area in dependence on the indentation depth d: [5]

$$A_p(d) = \frac{F}{H} \quad (1)$$

where

A_p – projected area of the indenter at the indentation depth d

F – test force

H - hardness

The function $A_p(d)$ is determined by the measurement of the indenter geometry. Due to the small size of the indenter (volume < 0.5 mm^3) scanning methods with a resolution in the nm-range are preferred. The area function is used to correct the indentation depth d of the indenter and correspondingly the hardness value which is calculated from d.

So far the area function was mainly applied in the nano and micro range of the instrumented indentation test. This means that only the surrounding of the indenter tip is scanned with an Atomic Force Microscope (AFM) in order to get a 3D data set of this part of the indenter. In our investigation we have transferred the idea of the area function to the description of the geometry of the whole Rockwell indenter.

Because for the Rockwell diamond indenter a height of 160 µm (in z-direction) is necessary for measurements starting from a hardness of 20 HRC, the scanning with an AFM tip is not possible, because the cantilever of the AFM tip would touch the indenter surface. Further in x and y directions (orthogonal to z) measurement ranges of about 400 µm are required. Therefore the scanning of the Rockwell diamond indenter was carried out with a dimensional measurement instrument based on a Nano Measuring Machine (NMM, SIOS Co.) [6][7][8]. The measurement range of the NMM is x = y = 25 mm and z = 5 mm, and the resolution of the laser interferometers which are used as directly traceable measurement systems amounts to 0.08 nm.

Four different sensor heads, namely a diamond stylus, a focus sensor and an AFM with conventional AFM probes and assembled cantilever probes, can be coupled to the instrument for fulfilling different measurement tasks [8]. Fig. 2 shows the setup for the scanning of the Rockwell indenters with a diamond stylus probe (type RFHTB-50, Mahr GmbH).

The surface was scanned along eight radial lines running over the apex of the indenter. The radial scan is realized by moving the indenter in a coordinated manner along the x- and y-axes simultaneously and the z position was controlled to keep the output of the stylus probe constant.. Therefore it is not necessary that the indenter is rotated during measurements. The 3D coordinates of measured points, taken during scanning by three high precision interferometers represent the 3D indenter surface.

Fig. 2. Setup for the measurement of the Rockwell indenters surface with a stylus probe on the NMM. The indenter is fixed on the scanning table which is moved in 3D.

The data processing comprised the following steps:

1) Morphological data procession (“erosion” of the 3D profiles to remove the “dilation” of the stylus tip)

The topography measured by a stylus profilometer is actually the dilation result of the true surface by the geometry of the stylus tip. Therefore the measured geometry has to be eroded with the known stylus tip shape to restore the “true surface” from the measured data.

The arrangement of the scan lines on the indenter surface is given in Fig. 3.

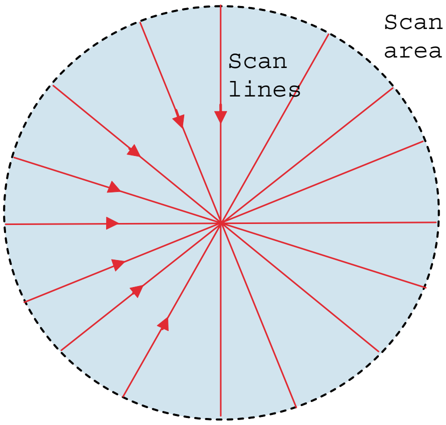

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Fig. 3. Arrangement of the radial scan lines going through the apex of the indenter.

In order to determine the radius of the spherical cap R_c and the cone angle θ of the indenter, point clouds of the spherical cap and the cone part have been extracted from the 3D geometry of the indenter. They are then fitted by least square method to a spherical cap and a cone from which R_c and θ are calculated.

3) Rotate the 3D points according to the fitted angles

In this procedure the orientation of the indenter is determined by the fitting process. When the indenter is measured, it is desirable that its axis coincides with the z-axis of the measurement instrument. However, a deviation of a few degrees may occur and will introduce a cosine error into the measurement results. Therefore we correct the influence of this angle deviation by coordinate rotation of the measured data set. The coordinate rotation can be calculated as:

$$\begin{bmatrix} x' \\ y' \\ z' \end{bmatrix} = \mathbf{M}_y \bullet \mathbf{M}_x \bullet \begin{bmatrix} x \\ y \\ z \end{bmatrix} \qquad (2)$$

is the matrix for rotating the vector around the y-axis by the angle Φ_y,

$$\mathbf{M}_y =$$

$$\mathbf{M}_x = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\phi_x & \sin\phi_x \\ 0 & -\sin\phi_x & \cos\phi_x \end{bmatrix}$$

is the matrix for rotating the vector around the x-axis by the angle Φ_x,

and the vectors $\begin{bmatrix} x \\ y \\ z \end{bmatrix}$ and $\begin{bmatrix} x' \\ y' \\ z' \end{bmatrix}$ are the coordinates of the measurement point before and after coordinate rotation, respectively.

4) Map the contour of the indenter at different indentation depths

As explained above, the area function is defined as the size of the projected area in dependence on the indentation depth d. In our study, the size of the projected area is described by its radius. In this way, the area function can also be interpreted as a radius function, but the term “area function” which is generally used to describe the real overall geometry is maintained in this paper. To calculate the area function, we firstly determine the contour points having the indentation depth d. Linear interpolation has been used to get the contour point if no measured point has exactly the indentation depth d. Two contour points can be determined from every measured profile, yielding altogether 16 contour points at each indentation depth. The arrangement of the contour points looks circular since the projection of the Rockwell indenter along its axis is a circle.

5) Fit the contour points to a circle (each 16 points per circle)

The calculated contour points are fitted by least square method to a circle for calculating its radius. So we get different radii at different indentation depths, i. e. the area function. This procedure is illustrated in Fig. 4.

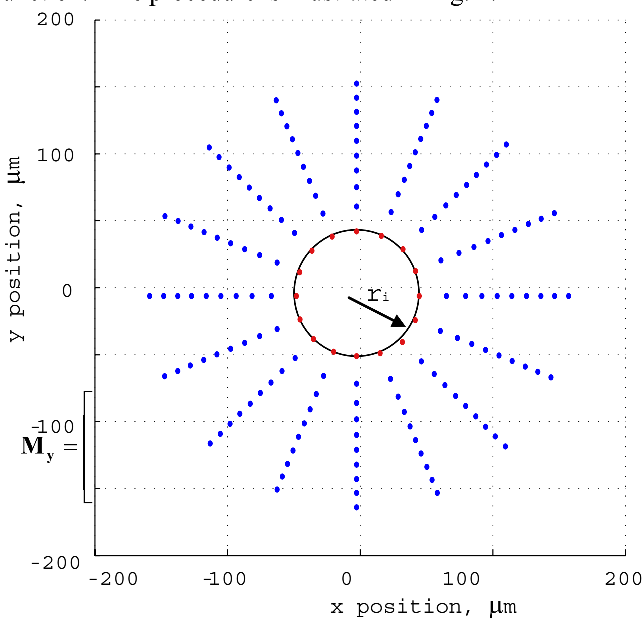

Fig. 4. Fitting the contour points having an indentation depth d to a circle. As shown by the innermost points, they are fitted by the least square method to a circle (solid line) which is the projected circle at the indentation depth d.

6) Plot the radius of the fitted circle over the indentation depth

An area function of the measured Rockwell indenter is shown in Fig. 5.

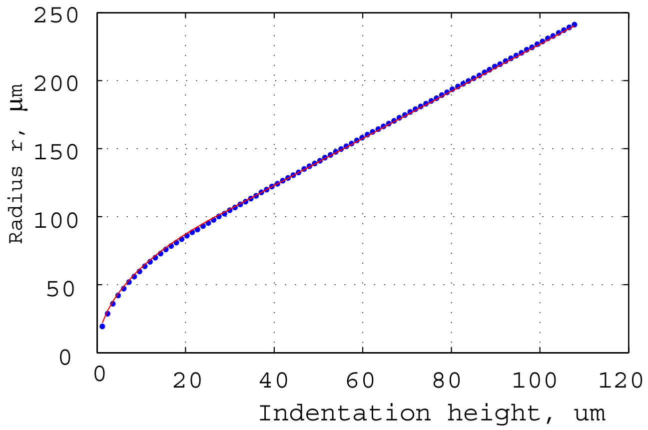

Fig. 5. Area function of a measured Rockwell indenter.

The dots are real measured values while the solid line represents an ideal Rockwell indenter.

7) Compare the calculated (measured) area function curve to the theoretical area function curve of the ideal geometry

From Fig. 5 one already gets the course of the calculated area function in comparison with the ideal geometry. Especially the figure clarifies that the area function of the ball cap region delivers smaller values than the ideal geometry. In detail the relationship between measured and ideal geometry is analyzed in the next step.

8) Calculate the deviation between the measured and the theoretical area function curves

Fig. 6 shows the deviation between the measured and the theoretical area function curves for the indenter No. 838. In this figure the radius r means the radius of the indenter shape vertical to the indenter axis.

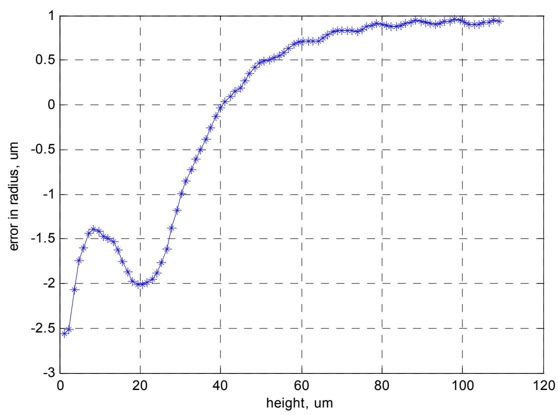

Fig. 6. Deviation between the measured and the theoretical area function curves of the Rockwell indenter No. 838.

Fig. 6 illustrates the pronounced irregular change of the radius over the indenter height of the ball cap ($d \leq 26.8$ µm).The rapid change of the radius deviation between 22 µm and 37 µm indicates a relatively large form deviation of the indenter. This region actually is the border between the ball cap and the cone frustum which is the most difficult part to be manufactured with high accuracy. Further, the negative values indicate a non-spherical shape of the ball cap. The cone exhibits some waviness from the polishing process of the indenter. Nevertheless, in this case, the deviations from the ideal geometry can be regarded as small.

4. COMPARISON OF THE INDENTER GEOMETRY BETWEEN GROUP STANDARD AND INDENTER AREA FUNCTION

The comparison of the two above presented approaches means the comparison of the correcture of hardness values based on the indenter area function with the indenter deviations derived from the group standard.

For the indenter area function it is necessary at first to convert the radius deviations into hardness deviations. The geometrical relationship between indentation depth deviations δd and radius deviations δr is presented in Fig. 7.

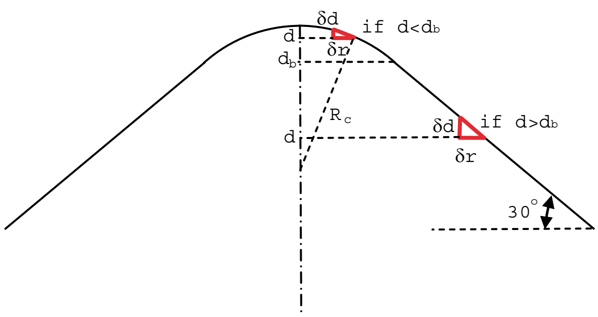

Fig. 7. Geometrical relationship between indentation depth deviation δd and radius deviation δr.

1) ball cap $\quad 0\ \mu m \leq r \leq 100\ \mu m$

$$\delta d = \frac{\sqrt{2Rh - h^2}}{R - h}\delta r \qquad (3)$$

2) cone part $\quad 100\ \mu m \leq r \leq 330\ \mu m$

$$\delta d = \tan 30° \cdot \delta r \qquad (4)$$

with R – ball cap radius,
r – radius perpendicular to the indenter axis,
δr – radius deviation.

For the determination of the hardness corrections one has to rely on the Rockwell hardness test procedure which is depicted in Fig. 8.

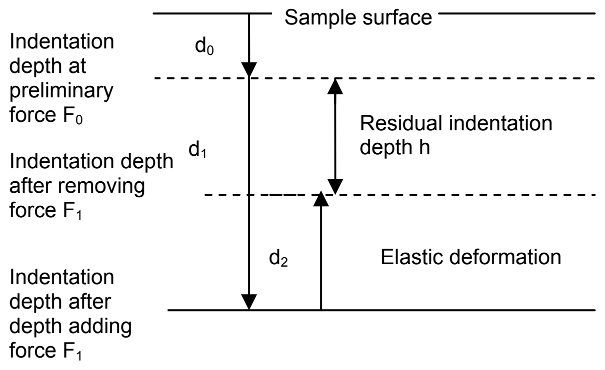

Fig. 8. Rockwell test procedure.

The Rockwell hardness *HR* is calculated from the residual indentation depth *h* as:

$$HR = N - \frac{h}{S} \tag{5}$$

where N is a constant and S the scaling value. For the Rockwell hardness scale HRC, N is 100 und S is 0.002. The unit of h and S is millimetre.

Based on Fig. 8, the Rockwell hardness is determined from the indentation depths of d_0 and $d_3 = d_0 + h$. If the geometry of the indenter deviates from its ideal shape, the measured indentation depths d_0 and d_3 will differ from the "true" indentation depths d_0' and d_3', leading to a measurement deviation in the hardness test.

The corrections δd_0 and δd_3 can be calculated at the indentation depths d_0 and d_3. Then the corrected hardness value HRC' amounts to:

$$HRC' = 100 - \frac{(d_3 + \delta d_3) - (d_0 + \delta d_0)}{0.002} \tag{6}$$
$$= HRC + \delta HRC$$

where HRC is the originally measured hardness value and $\delta HRC = \frac{\delta d_0 - \delta d_3}{0.002}$ is the correction value on the HRC value, δd_0 *and* δd_3 are in millimetre.

Based on the calculations according to equations (3) to (6), Fig. 9 depicts the deviations from the mean value of the corrected hardness values of the investigated three Rockwell indenters.

Fig. 9 clarifies that by the correction of the hardness values based on the area functions as a preliminary result the maximum deviation is reduced to < 0.15 HRC. For the lower hardness levels from 20 HRC to 40 HRC this deviation is only < 0.10 HRC. The maximum deviation of <0.15 HRC occurs at small indentation depths which are limited to the ball cap region. Further, the mean hardness deviation of this group standard is reduced from 0.11 HRC to 0.06 HRC. This means, that compared with the group standard, by calibration of Rockwell diamond indenters with the NMM the to be corrected specific indenter deviations can be further reduced.

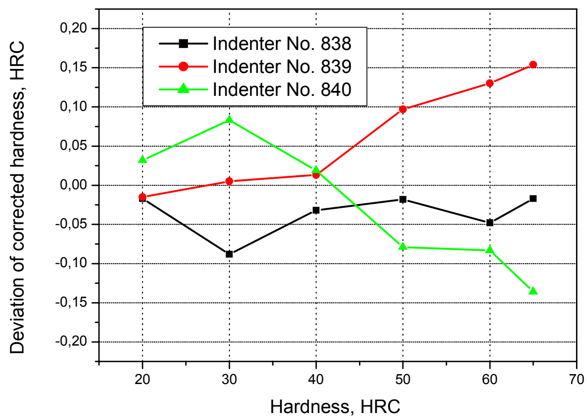

Fig. 9. Hardness deviations from the corrected hardness values of three Rockwell diamond indenters obtained for six different hardness levels.

5. SUMMARY

The investigation of the two above presented methods for the determination of the geometry of Rockwell diamond indenters opens a possibility to improve the characterization of indenters. The group standard allows to achieve a stable Rockwell hardness scale. The indenter is characterized at several hardness levels with hardness reference blocks. On this basis a regression curve can be fitted for every hardness value within the measured range.

On the other hand, the area function obtained from the NMM delivers more detailed information about the specific geometrical indenter deviations. In this case the remaining hardness deviations are still smaller than those of the group standard. For this purpose a high accuracy stylus profilometer has been set up based on a precision nano measuring and positioning machine. In its configuration, the indenter is scanned in 3D and is detected by a position stationary stylus probe. The actual positions of the indenter are measured by three embedded miniature laser interferometers, offering high measurement accuracy at nanometre level and direct measurement traceability. In addition a special radial scan function has been realized so that the indenter can be scanned radially with profilers through its apex, providing more topographical details about its ball cap in the measurement result. Data evaluation of the 3D geometry for calculating the indenter area function has been introduced.

The correction of hardness test results on the basis of the indenter area function has been described. For a group of three indenters investigated in this study, the correction reduces the mean measurement deviation of the group standard from 0.11 HRC to 0.06 HRC, what confirms the effectiveness of our proposed correction method.

Future investigations are orientated at getting a deeper understanding of both methods and at correction methods for Rockwell diamond indenters for all standardized Rockwell scales. It seems to be meaningful to get still more information about the actual ball cap geometry.

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