FORM ERROR AND HARDNESS PERFORMANCE OF ROCKWELL DIAMOND INDENTERS

J. Song [1], S. Low [1] and L. Ma [2]

[1] National Institute of Standards and Technology
Gaithersburg, MD 20899, USA
[2] Department of Mechanical Engineering and Mechanics
Drexel University, Philadelphia, PA 19104, USA

Abstract: The influences of form errors on hardness performance of Rockwell diamond indenter are discussed. Experimental results are introduced. The Finite Element Analysis (FEA) method is used to simulate the hardness measurement process. The effect of tip radii and cone angles on hardness performance is obtained from our FEA model. It is suggested that FEA could be used to establish a relationship between the microform geometry and the hardness performance of Rockwell indenters, and to predict offsets in hardness readings based on the geometry parameters of the indenter, the testing cycle and the mechanical properties of the testing material.

Keywords: Rockwell diamond indenter, form error, finite element analysis, FEA

1   INTRODUCTION

The Rockwell hardness test is the most widely used mechanical test method for metal products. However, Rockwell hardness scales are not unified in different countries. An international effort is being made to establish a worldwide unified Rockwell hardness scale with metrological traceability. Two key steps include: (A) Establishing standard Rockwell indenters based on geometric calibrations and hardness performance verification; (B) Establishing a common testing cycle based on an international agreement [1].

The Rockwell diamond indenter is a diamond cone with $120°$ cone angle and $200 \ \mu m$ tip radius. Other geometric parameters of the Rockwell indenter include profile deviations from the least squares radius, cone flank straightness, holder axis alignment error and surface roughness. These geometric parameters affect the performance of Rockwell indenters. The influence of tip radius and cone angle was theoretically and experimentally investigated by Barbato, et al [2,3]. However, it was previously difficult to measure and quantify form errors of Rockwell diamond indenters, and to determine their influence on the hardness performance of Rockwell indenters until a measurement system was developed for calibrating the microform geometry of Rockwell indenters [4].

In this paper, we discuss the influences of form errors on hardness measurements of Rockwell indenters. We discuss geometry parameters in section 2. We discuss some measurements and testing results in section 3, and we introduce new theoretical investigations of these influences using finite element analysis (FEA), where we describe some basic input parameters, initial results and future work in section 4.

2   GEOMETRY AND TOLERANCE OF ROCKWELL DIAMOND INDENTER

For a calibration grade Rockwell indenter, geometry parameters and tolerances are defined as [5-7]:

- Tip radius: Mean: $(200 \pm 5) \ \mu m$; maximum and minimum: $(200 \pm 7) \ \mu m$; profile deviations from the least squares radius: $\pm 2 \ \mu m$;

- Cone angle: Mean: $(120 \pm 0.1)°$; maximum and minimum: $(120 \pm 0.17)°$; cone flank straightness: $0.5 \ \mu m$;
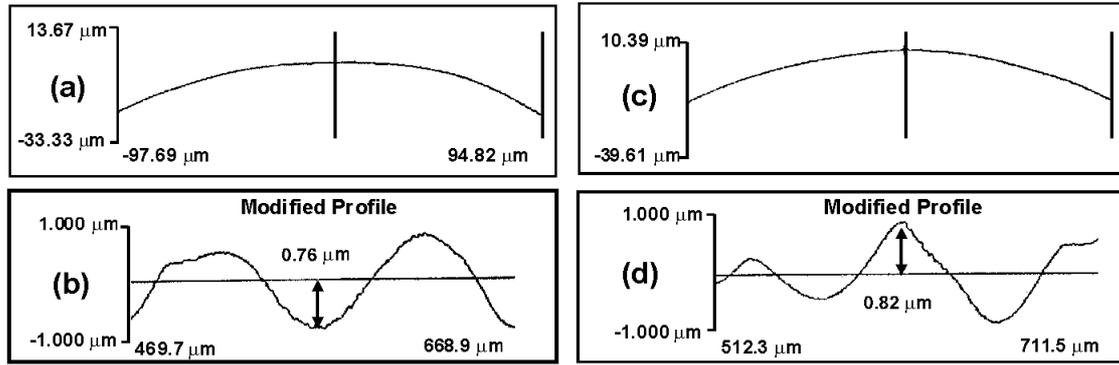
- Holder axis alignment error: $\pm 0.3°$.

Figure 1. "Flat" and "sharp" shaped Rockwell indenters:
(a) A "flat" shaped indenter; (b) After least squares arc fitting, a 0.76 µm central profile valley can be seen; (c) A "sharp" shaped indenter; (d) After least squares arc fitting, a 0.82 µm central profile peak can be seen.

Table 1. Geometrical Measurement Results of Nine Rockwell Diamond Indenter from NIST and NRLM

Indenter No.	Spherical tip			Cone surface			Holder axis	Surface
	Least squares radii		Prof. dev.	Cone angle		Cone flank	alignment	roughness
	Mean (Unc'ty) (µm)	Max. Min. (µm)	Max. peak Max. val'y (µm)	Mean (Unc'ty) (°)	Max. Min. (°)	stra'tness Max. (µm)	error and unc'ty (°)	Ra mean Ra max. (µm)
NIST 3309	198.34 (±2.04)	199.66 196.30	0.43 0.46	119.98 (±0.03)	120.00 119.96	0.49	0.03 (±0.03)	0.0035 0.0038
NIST 3581	199.06 (±1.97)	200.69 197.63	0.40 0.29	120.00 (±0.02)	120.01 119.98	0.42	0.08 (±0.02)	0.0043 0.0045
NIST 3488	200.55 (±0.75)	201.05 199.92	0.34 0.25	120.07 (±0.02)	120.08 120.06	0.44	0.03 (±0.02)	0.0063 0.0097
NIST 3313	200.82 (±2.22)	202.28 198.74	0.51 0.46	120.07 (±0.06)	120.10 120.01	0.40	0.04 (±0.03)	0.0053 0.0077
NRLM 13392	197.25 (±1.56)	198.45 196.05	0.92 0.51	120.03 (±0.03)	120.04 120.00	0.34	0.08 (±0.03)	0.0049 0.0055
NRLM 22629	199.07 (±1.42)	200.14 198.16	0.27 0.35	120.01 (±0.02)	120.02 119.99	0.37	0.12 (±0.02)	0.0035 0.0036
NRLM 13217	200.38 (±2.40)	202.75 198.72	0.24 0.37	120.11 (±0.03)	120.14 120.08	0.15	0.06 (±0.02)	0.0043 0.0047
NRLM 26632	201.34 (±3.26)	203.91 199.25	0.22 0.38	120.21 (±0.03)	120.24 120.19	0.17	0.03 (±0.02)	0.0036 0.0038
NRLM 32855	202.43 (±2.63)	204.33 201.71	0.26 0.46	119.89 (±0.06)	119.94 119.84	0.21	0.08 (±0.03)	0.0036 0.0038

3   FORM ERROR AND ITS INFLUENCE ON HARDNESS PERFORMANCE

Because of the anisotropy of diamond, it is difficult to make a perfect spherical shape on Rockwell indenters. One manufacturer uses the (110) crystal axis orientation. Their Rockwell indenters measured in our laboratory show a flat-shaped tip (see Fig. 1a) with a four-lobed surface. After the least squares arc fitting, a profile valley can be seen (Fig. 1b). . After the least squares arc fitting, a profile valley can be seen (Fig. 1b).Another manufacturer uses (111) orientation, their Rockwell indenters show a sharp-shaped tip (see Fig. 1c) with a three-lobed surface. . After the least squares arc fitting, a profile peak can be seen (Fig.1d). Although these two types of Rockwell indenter have the same overall tip radius and cone angle, their hardness performances may show significant differences. These form errors are expected to affect the performance of Rockwell indenters, especially for HR tests at small loads (HR45N, HR30N, and HR15N).

In order to achieve hardness measurement agreement, not only must the tip radius and cone angle be tightly controlled, but also the geometrical form errors as well. In 1995, NIST established a group of 9 indenters with tightly controlled geometric tolerances. The mean radii of the 9 indenters range from 198.34 µm to 202.90 µm. The mean cone angles range from 119.94° to 120.07°. The maximum profile deviations from the least squares radius range from –0.52 µm to +0.65 µm, and the cone flank straightness ranges from 0.40 µm to 0.75 µm. This set of 9 indenters was tested at the NIST standardized deadweight hardness machine [1]. The total range of deviations is (–0.17 to +0.23) HRC from the mean at 25, 35, 50 and 60 HRC [1]. This result shows that improving geometric uniformity, perhaps including control of the form errors of Rockwell indenters, can significantly improve hardness measurement agreement. A Rockwell indenter selected from this group of 9 indenters is currently used as the NIST primary indenter for Rockwell hardness calibrations.

Another group of 9 indenters from NIST and NRLM (National Research Laboratory of Metrology, Japan) were made by two diamond manufacturers. The NIST indenters used the (111) crystal axis
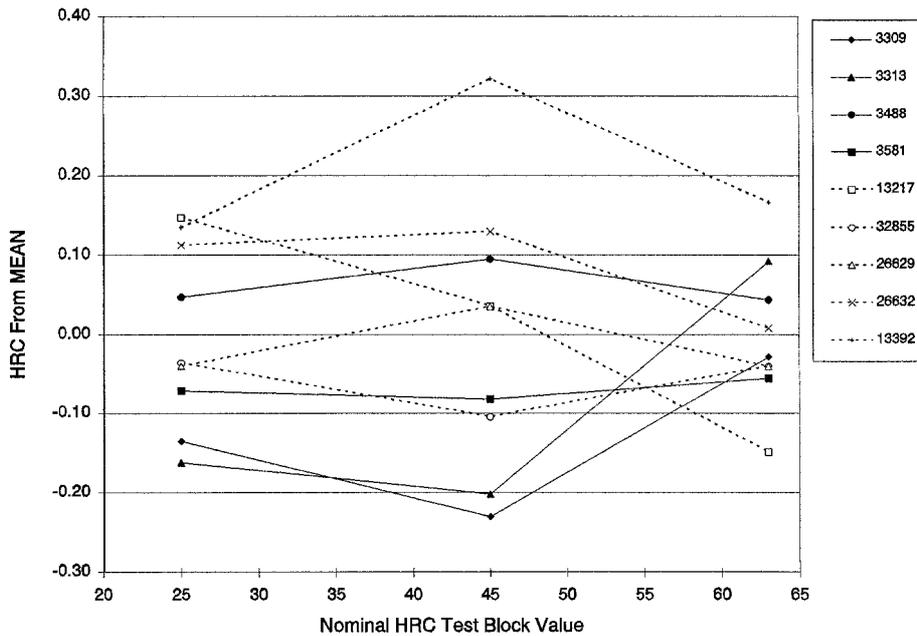

Figure 2. Performance comparisons of nine indenters made by two manufacturers. The variation range is (-0.23 to + 0.32)HRC

orientation with sharp-shaped indenter tips, and the NRLM indenters used the 110 orientation with flat-shaped tips. Measurement results of their microform geometry are shown in Table 1. The mean tip radii of the 9 indenters range from 197.25 µm to 202.43 µm, the mean cone angles range from 119.89° to 120.21°. The maximum profile deviations from the least squares radii range from -0.51 µm to +0.92 µm, and the cone flank straightness ranges from 0.15 µm to 0.49 µm.

For all nine indenters, the hardness performance tests show a total variation range of (-0.23 to +0.32) HRC from the means at 25 HRC, 45 HRC and 63 HRC (see Fig. 2). However, one indenter, numbered 13392 with significant profile deviation, shows performance bias with respect to the other eight indenters (see Table 1 and Fig. 2, No.13392 indenter). When the data for this indenter are removed, the other eight indenters show a performance variation range of ±0.19 HRC from (25 to 63) HRC [1]. This set of data once again demonstrates the influence of form errors on the hardness performances of Rockwell indenters.

4   FINITE ELEMENT ANALYSIS AND HARDNESS PERFORMANCE PREDICTION

We are working on the finite element analysis (FEA) methods for analyzing and predicting the effects of form errors of Rockwell indenters on hardness performance. This method can provide insight into the indentation process. In addition, it allows us to isolate the contributions of different hardness measurement parameters including those from indenter geometry, testing cycle, and mechanical property of tested material.

In our FEA simulation, a commercial FEA software with large elastic-plastic strain capability was used. For the time being, our FEA model takes advantage of axial symmetry of a conical indenter and
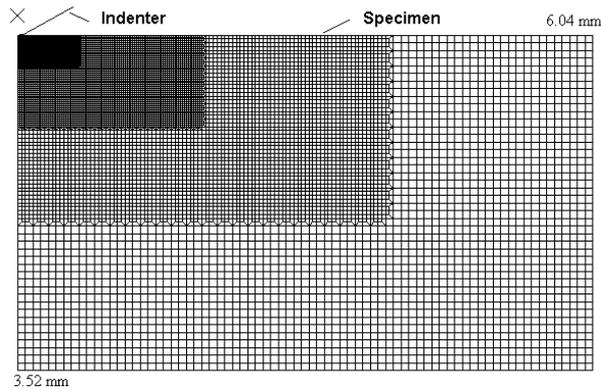

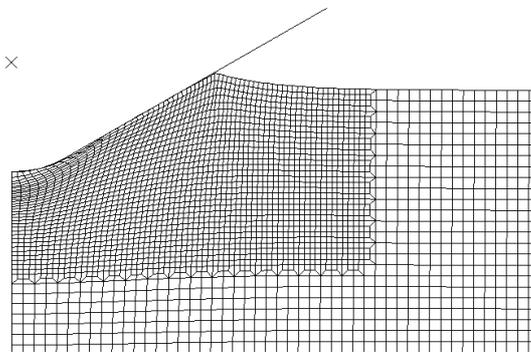**Figure 3.** Finite element analysis mesh model, ($\times$) is the reference point of the indenter

Figure 5. Scheme of testing cycle

Figure 4. Shape of maximum indentation
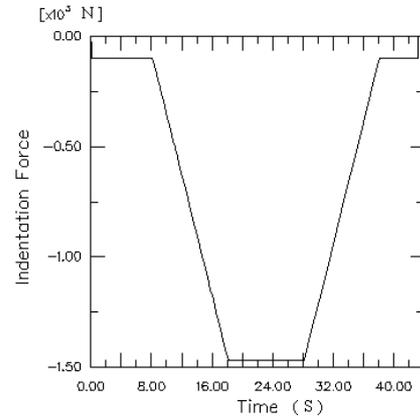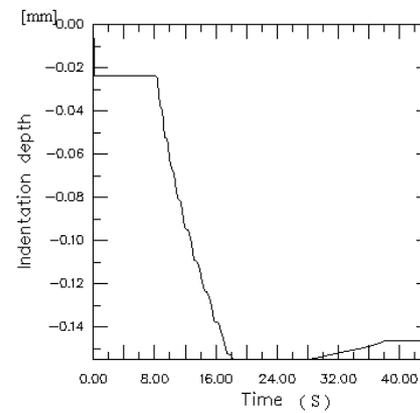

Figure 6. Scheme of indentation depth

cylindrical specimen. Only one radial-axial plane is modeled which significantly reduces the complexity of the simulation. The diamond indenter is modeled as a rigid body with different cone angles and tip radii. A cylindrical specimen with sufficiently large size is used to eliminate boundary effects. The specimen is modeled with a homogeneous elasto-plastic material. The friction coefficient between the specimen and the indenter is assumed to be 0.1. The type and distribution of the FEA mesh is shown in Fig. 3. The whole mesh is an arrangement of quadrilateral, four-node axisymmetric elements. To save computing time, the mesh becomes coarser with distance away from the indenter. Fig. 4 shows the mesh at maximum deformation. The boundary conditions include: 1) restricting the bottom of the specimen from moving downwards, 2) restricting the mid-plane of the specimen from moving along the x-direction and 3) restricting the indenter from moving along x-direction and rotating. A concentrated force is applied at the reference point of the indenter which is the center of the tip radius. The test cycle is shown in Fig. 5. After the FEA simulation, we can obtain a plot of indentation depth with change of time, as shown in Fig.6. From this figure, we can obtain the HRC value.

To test the effect of indenter cone angles and tip radii, FEA simulations with different indenter cone angles and tip radii are performed on the same material with a hardness around HRC39, and the same test cycle shown in Fig. 5. The results are shown in Fig. 7 and Fig. 8. In Fig. 7, we chose cone angles with the standard value of 120^0, and the tip radii were changed. From Fig. 7, we can see that as the tip radius increases, the HRC values increase linearly around the mean value. In Fig. 8, the tip radii were kept at the same standard value of 200 μm, and the cone angles were changed. We can see that as the cone angle increases, the HRC value also increases linearly. These observations are consistent with Dr. Barbato's results [8,9].

For our future work we plan to improve the FEA model so that we can input the indenter geometry directly from the measurements. This includes the macro geometry parameters such as tip radius and cone angles, and micro geometry parameters such as different form errors. In this way, the effect of

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form errors on the performance of Rockwell indenters can be theoretically and experimentally studied. Based on these studies, it is possible to design reasonable tolerances for the form errors of Rockwell indenters. In addition, the improved FEA model will also include time-dependent mechanical properties of the test material, such as strain rate sensitivity and creep. The expected goal is to simulate the hardness performance of the Rockwell indenters and predict variations of the hardness performances based on the geometry of the indenter, the testing cycle, and the mechanical properties of the test material.
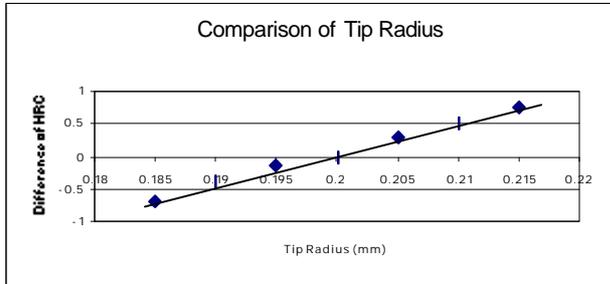

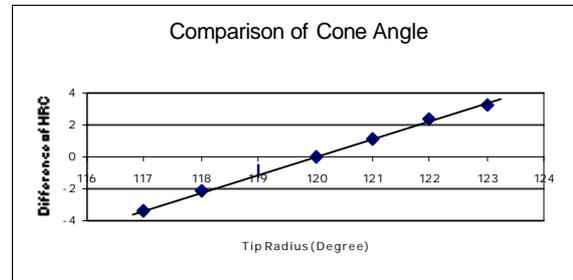**Figure 7.** Plot of the HRC difference with the change of cone angle

Figure 8. Plot of the HRC difference with the change of tip radius

5   SUMMARY

Form errors affect the hardness performance of Rockwell indenters. Experimental results show that tightly controlled tip radii, cone angles and form errors can significantly improve the hardness measurement agreement of Rockwell indenters. Finite element analysis can be used for analyzing the effects of different geometry parameters, and eventually to predict the performance of Rockwell diamond indenters.

ACKNOLEDGEMENT

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AUTHORS: J. SONG, S. LOW, A117, Metrology, NIST, Gaithersburg, MD 20899-8212, USA. Phone: (301) 975-3799, Fax: (301) 869-0822, e-mail: junfeng.song@nist.gov and L. MA, Department of Mechanical Engineering and Mechanics, Drexel University, Philadelphia, PA 19104, USA