Military Technical College
Kobry El-Kobbah,
Cairo, Egypt

14th International Conference on
Applied Mechanics and
Mechanical Engineering.

The Effect of Indenter Geometrical Errors on the Accuracy And Uncertainty of Brinell Hardness

By

R. Hegazy * M.Ibrahim ** A. Abuelezz *** M. El-Sherbiny◇

Abstract:

This paper reports work carried out to determine the influence of the ball indenter geometrical errors on the accuracy of Brinell hardness measurements. Indenters with nominal diameters of 1, 2.5, and 5 mm diameter are tested. Fifteen balls are considered for each nominal diameter. The roundness error of each ball is measured. The diameters of the balls were measured by profile projector and the roundness error was measured by CMM machine. The influence of the ball geometry on the accuracy of hardness is investigated. Six calibrated reference hardness-test blocks are used to perform Brinell hardness test using the 45 selected balls. The results show that the roundness error considerably affects the accuracy of the hardness measurement.

Keywords:

Brinell hardness, Brinell Indenter geometry ,

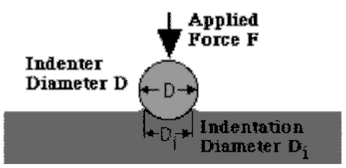
* Research Assistant, National Institute of Standards, Egypt
** Assoc. Prof, National Institute of Standards, Egypt
*** Professor, National Institute of Standards, Egypt
*** Professor, Faculty of Engineering, Cairo University, Egypt

1. Introduction:

Hardness is a measure of a material's resistance to local deformation caused by an indentation from a hard body. The most common indentation hardness tests in industry are Brinell, Vickers, and Rockwell.

1-1 Brinell hardness test

The Brinell hardness test method consists of indenting the test material with a hardened steel or carbide ball subjected to a load. The diameter of the indentation left in the test material is measured with a low powered microscope. The Brinell hardness number is calculated by dividing the load applied by the surface area of the indentation as shown in equation (1).



$$BHN = \frac{F}{\frac{\pi}{2} D \cdot (D - \sqrt{D^2 - D_i^2})} \quad (1)$$

The diameter of the impression is the average of two readings at right angles. A well structured Brinell hardness number reveals the test conditions, and looks like this, "75 HB 1/30/30 which means that a Brinell hardness of 75 was obtained using a 1mm diameter hardened steel ball with a 30 kilogram load applied for a period of 30 seconds respectively. On tests of extremely hard metals, a tungsten carbide ball is substituted for the steel ball. Compared to the other hardness test methods, the Brinell ball makes the deepest and widest indentation, so the test averages the hardness over a wider amount of material, which more accurately accounts for multiple grain structures and any irregularities in the uniformity of the material [1].
The “true value” of hardness is achieved by the “ideal operator”, using the “ideal standards hardness calibration machine” with the “ideal indenter” and working to the standards without any error [2]. In practice, it is impossible to realize the true value of the hardness scale, because the hardness machine and indenter cannot be manufactured and calibrated without tolerances. However, by controlling and reducing such tolerances of the reference standards, both random and systematic errors and their uncertainty contribution to the hardness scales can be minimized.
It has been recognized that different indenters, of nominally similar geometry, can lead to large variations in measured hardness values [3]. It has been identified that Brinell indenter morphology will contribute to the uncertainty in the hardness measurement. Therefore, it would be advisable to investigate these effects. The work described in this paper aims to quantify the effect of different indenter geometries on measured Brinell hardness.

2-Experimental set up

The diameters of fifteen balls are measured by the profile projector P J – 250 shown in Fig (1). It is Mitutoyo bench top single lens mount, model PJ250, with 20x Objective, 9" diameter rotating projection screen ,and, 2-Axis digital micrometer stage. It utilizes surface reflection attachment and graduated chart ring.

Figure (1): *Mitutoyo Profile projector*

The roundness of ten indenters from each nominal size are measured by PRISMO Carl Zeiss Coordinate Measuring machine (CMM), verified according to ISO 10360 which is shown in Fig (2).

Fig (2): *PRISMO CMM*

The roundness deviation of measured circumferential circles is based on the Egyptian standard ES-NO.:779[4] with the following strategy:

No of points over each circumference circle: 100 to 120 point
Stylus tip radius: 0.75mm
Probing force: 100 mN

Scanning speed: 1 mm/sec
Reference circle: Least square circle (LSC)

The measurement of the roundness deviation is taken around five circles at five different locations randomly distributed over the surface of each ball.

3-Results

3-1 Measuring the diameter of the balls:

Fifteen balls from each nominal diameter were measured. Five measurements were taken for each ball randomly from different positions as shown in tables 1-3

(Table I): *diameters of the balls with 5 mm nominal diameter*

Ball No.	Measure(1) mm	Measure(2) mm	Measure(3) mm	Measure(4) mm	Measure(5) mm	Average mm
1	5.012	5.015	5.004	5.016	5.014	5.0122
2	5.006	5.007	5.001	4.995	4.991	5.000
3	4.99	5.009	5.007	5.005	5.009	5.004
4	5.006	5.005	5.006	5.004	5.005	5.0052
5	5.001	5.002	4.995	5.001	5.001	5.000
6	5.001	4.997	4.998	4.996	4.994	4.9972
7	5.002	5.001	4.995	4.997	4.899	4.9788
8	4.998	4.998	4.997	4.995	5	4.9976
9	4.987	4.991	4.985	4.991	5.001	4.991
10	4.99	5.001	5.002	4.996	4.986	4.995
11	5.009	5.012	5.008	5.007	5.009	5.009
12	5.014	5.007	5.004	5.016	5.015	5.011
13	5.005	5.014	5.013	5.014	5.012	5.012
14	5.005	5.009	5.007	5.006	5.008	5.007
15	4.998	5.005	5.007	5.011	5.004	5.005

(Table 2)**:** *Diameters of the balls with 2.5mm nominal diameter*

Ball No.	Measure(1) mm	Measure(2) mm	Measure(3) mm	Measure(4) mm	Measure(5) mm	Average mm
1	2.504	2.505	2.501	2.501	2.501	2.5024
2	2.504	2.504	2.502	2.505	2.504	2.5038
3	2.504	2.5	2.5	2.502	2.499	2.501
4	2.499	2.495	2.503	2.502	2.504	2.5006
5	2.503	2.505	2.503	2.502	2.504	2.5034
6	2.496	2.502	2.499	2.494	2.504	2.499
7	2.494	2.491	2.501	2.502	2.492	2.496
8	2.499	2.498	2.503	2.502	2.498	2.5
9	2.503	2.495	2.5	2.498	2.499	2.499
10	2.495	2.497	2.502	2.497	2.5	2.498

11	2.504	2.502	2.503	2.505	2.506	2.504
12	2.509	2.507	2.508	2.51	2.512	2.509
13	2.501	2.501	2.506	2.507	2.508	2.505
14	2.502	2.503	2.499	2.498	2.498	2.500
15	2.508	2.509	2.509	2.515	2.514	2.511

(Table 3): *Diameters of the balls with 1mm nominal diameter*

	Measure(1) mm	Measure(2) mm	Measure(3) mm	Measure(4) mm	Measure(5) mm	Average mm
1	1.005	1.002	1.003	1.004	1.002	1.0032
2	1.012	1.004	1.002	0.998	1.001	1.0034
3	1.001	1.001	1.002	1.008	1.019	1.0062
4	1.008	1.006	0.997	0.999	0.998	1.0016
5	1.006	1.004	1.004	1.004	1.007	1.005
6	0.997	0.997	1.001	0.994	1.001	0.998
7	0.992	0.993	1.004	0.999	0.997	0.997
8	0.985	0.989	0.995	0.998	0.988	0.991
9	1.003	1.004	1.001	0.998	0.999	1.001
10	0.985	0.986	0.989	0.99	0.99	0.988
11	1.008	1.009	1.011	1.014	1.013	1.011
12	1.006	1.005	1.011	1.012	1.011	1.009
13	1.009	1.008	1.015	1.016	1.012	1.012
14	1.016	1.017	1.018	1.018	1.016	1.017
15	1.009	1.008	1.004	1.007	1.007	1.007

As shown in tables 1-3, balls of 5 mm nominal diameter vary from 4.9788mm to 5.0122 mm. The variations of the diameters yield a range of 0.0334mm; which is 0.6% of the nominal diameter. For balls 2.5 the range of the diameter variation is 0.015 mm which equal to 0.6% from the nominal diameter, while for the balls with nominal diameter 1 mm the range is 0.029 mm, rising up to 2.9% from the nominal diameter, It also indicate that the percentage variations is much higher at smaller indenter sizes.

3-2 Roundness error

Ten balls from each nominal diameter 5, 2.5, and 1mm were used to measure the roundness error by CMM machine, as shown from tables 4-6.

(Table 4): *the roundness error of the 5mm balls*

No.	Diameter mm	Roundness error μm
1	5.0122	2.5
2	5	2.4
3	5.004	2.2
4	5.0052	2.2
5	5	2.4
6	4.9972	3.2

7	**4.9788**	**2.4**
8	**4.9976**	**2.2**
9	**4.991**	**1.9**
10	**4.995**	**2.3**

(Table 5)*: *The roundness error of the 2.5 mm balls

Ball No.	Diameter mm	Roundness error µm
1	2.5024	2.6
2	2.5038	3.8
3	2.501	3.3
4	2.5006	4.5
5	2.5034	5.4
6	2.499	7.3
7	2.496	5.2
8	2.5	2.7
9	2.499	7.7
10	2.4982	7.2

(Table 6)*: *The roundness error of the 1mm balls

Ball No.	Diameter mm	Roundness error µm
1	1.0026	5.1
2	1.0034	5.4
3	1.0062	6.1
4	1.0016	6.5
5	1.005	5.2
6	0.998	7.2
7	0.997	7.2
8	1	7.8
9	1.001	8.2
10	0.988	7.1

It is shown that the maximum roundness error of the balls with nominal diameters of 5, 2.5, and 1mm are 3.2, 7.7, 8.2 µm respectively.

3-3 The effect of the ball diameter on the hardness value:

Each ball from all nominal diameters was used to perform hardness test on two different calibrated reference blocks with two different hardness values 219 and 450 HB. Forty-five balls were used to perform hardness test. Each test was carried out with five indentations. The average of five indentations is obtained. The tests were performed according to the

ISO/CD 5606-1[5] .Tables 7-12 , and figures 3-8 show the effect of ball diameter in Brinell hardness values.
The confidence level of 95% is taken for the analysis of the hardness values as limits of ± 2Se where (Se) is the standard error of estimate which is calculated from the following equation (2) [6]:

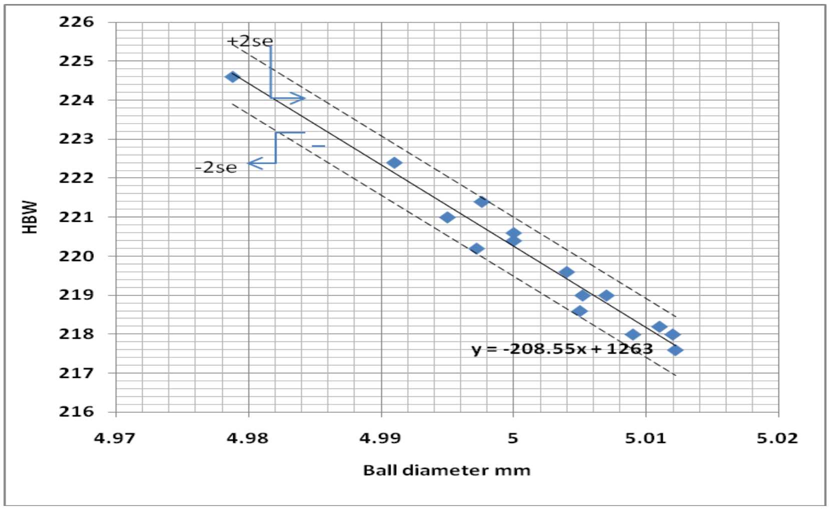
$$Se = \sum_{n}^{i=1} \sqrt{\frac{(yi - yc)^2}{n-2}} \qquad (2)$$

Se=

Where
yi: is the experimental hardness value
yc: The calculated hardness value from the equation of the trend line
n: the No. of readings =15

(Table 7): *Effect of ball diameter on hardness No, 219±2 HBW*

Ball diameter mm	Range mm	HB1	HB2	HB3	HB4	HB5	Average HB
5.0122	0.012	218	217	217	218	218	217.6
5	0.016	222	220	220	219	221	220.4
5.004	0.019	220	218	220	219	221	219.6
5.0052	0.002	219	220	218	219	219	219
5	0.007	220	220	220	221	222	220.6
4.9972	0.007	221	221	220	220	219	220.2
4.9788	0.103	225	224	225	225	224	224.6
4.9976	0.005	222	221	222	221	221	221.4
4.991	0.016	221	222	223	223	223	222.4
4.995	0.016	222	221	221	221	220	221
5.009	0.005	219	216	219	218	218	218
5.011	0.012	218	217	219	219	218	218.2
5.012	0.009	219	218	217	219	217	218
5.007	0.004	219	219	218	220	219	219
5.005	0.013	218	220	218	219	218	218.6



(Fig 3): *Relation between ball diameter of the indenter and hardness No (Ball 5mm 219 HBW)*

(Table 8): *Effect of ball diameter on hardness No, Ball 5mm, 449±2HBW*

Ball diameter mm	Range mm	HB1	HB2	HB3	HB4	HB5	Average HB
5.0122	0.012	448	447	446	447	447	447
5	0.016	450	450	450	451	449	450
5.004	0.019	448	450	448	449	449	448.8
5.0052	0.002	448	449	448	449	449	448.6
5	0.007	450	450	449	451	449	449.8
4.9972	0.007	450	451	451	452	450	450.8
4.9788	0.103	456	458	457	458	456	457
4.9976	0.005	451	452	452	452	451	451.6
4.991	0.016	452	452	453	453	452	452.4
4.995	0.016	452	452	452	453	453	452.4
5.009	0.005	448	447	447	447	448	447.4
5.011	0.012	447	447	445	449	447	447
5.012	0.009	448	446	446	447	447	446.8
5.007	0.004	448	448	447	449	447	447.8
5.005	0.013	448	450	448	449	449	448.8

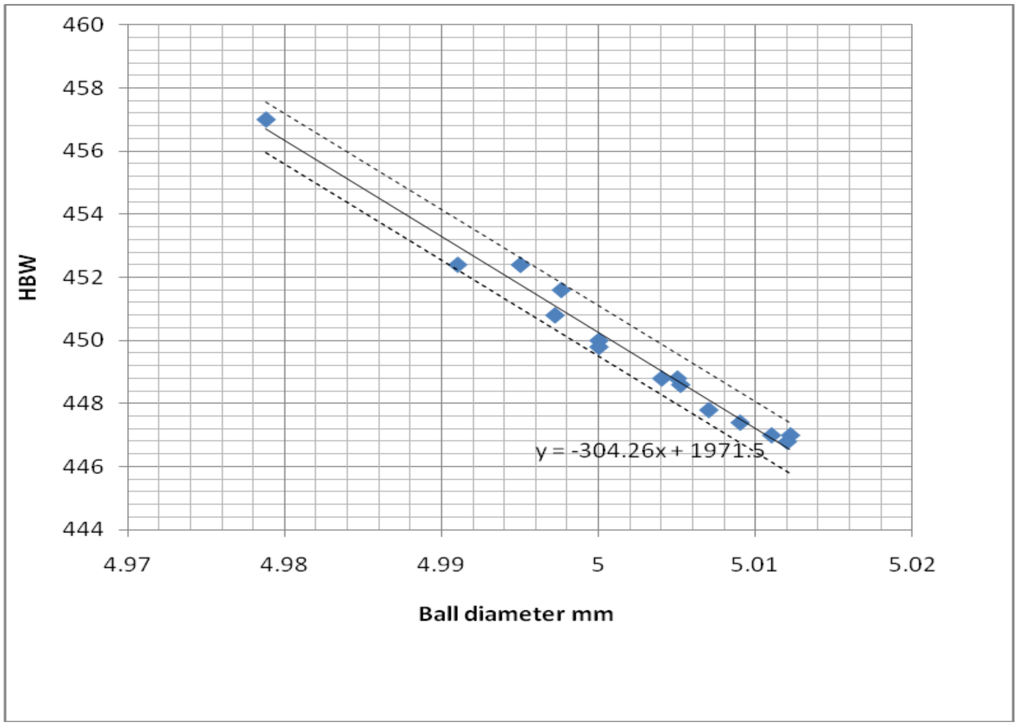
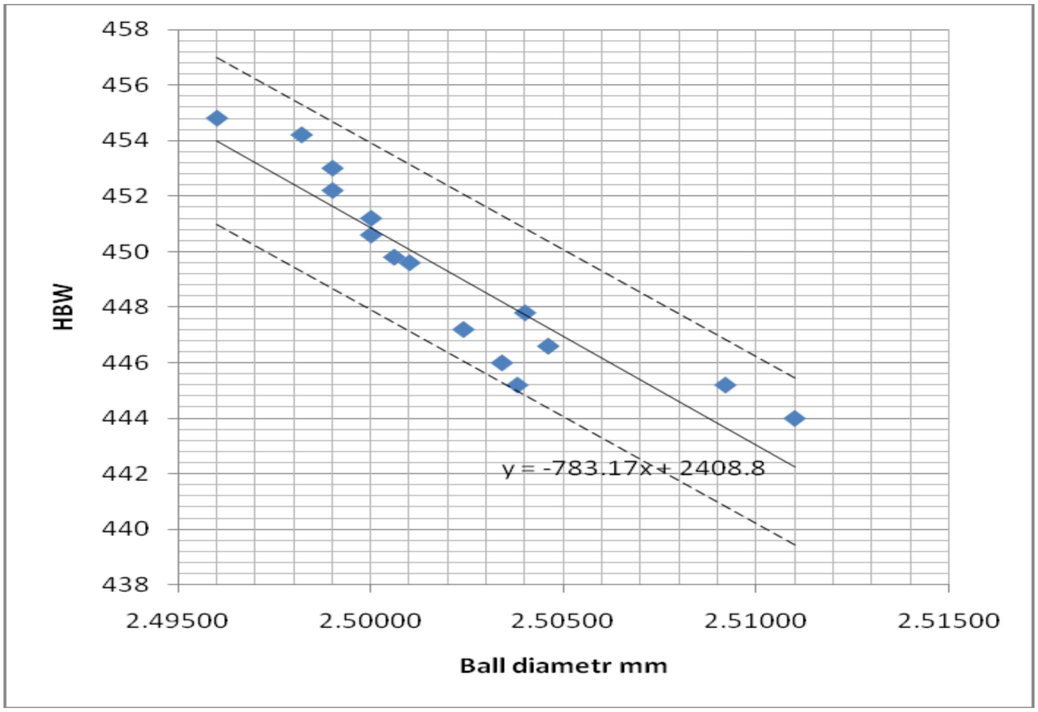


Fig 4 Relation between ball diameter of the indenter and hardness No (Ball 5mm 449HBW)

(Table 9): *Effect of ball diameter on hardness No, Ball 2.5mm, 449±1.5HBW*

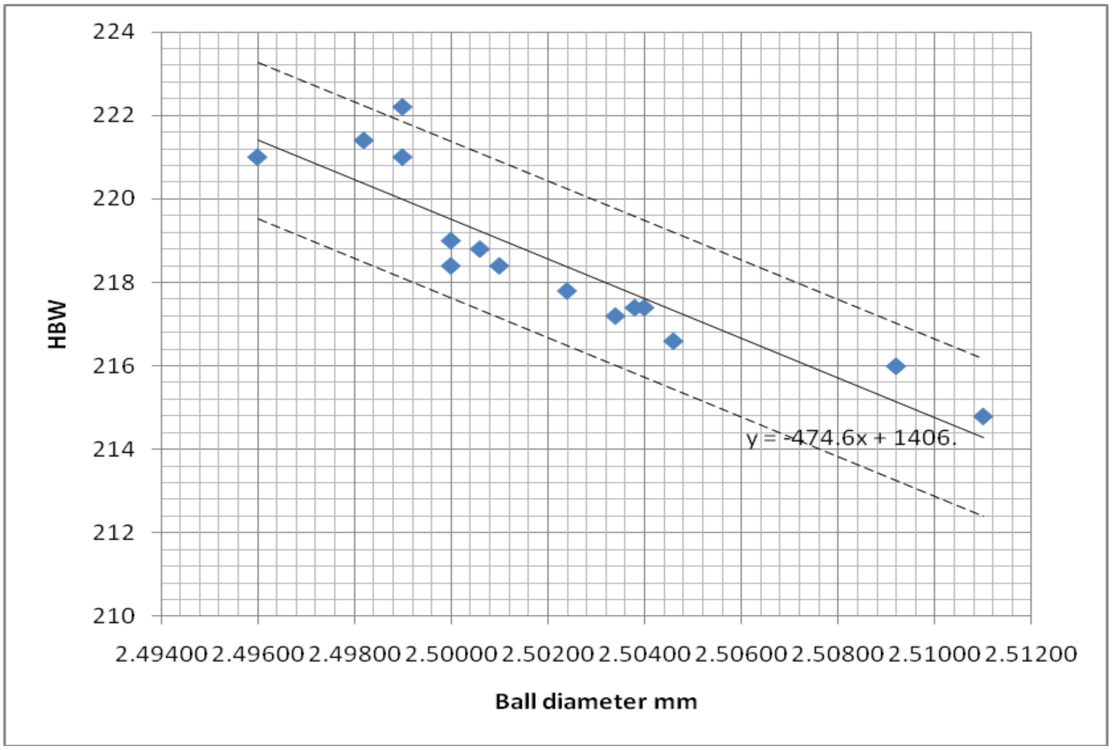
Ball diameter mm	Range mm	HB1	HB2	HB3	HB4	HB5	Average HB
2.50240	0.004	448	447	448	449	446	447.6
2.50380	0.003	445	448	447	448	446	446.8
2.50100	0.005	449	449	450	450	450	449.6
2.50060	0.009	449	450	451	450	449	449.8
2.50340	0.003	447	446	448	447	447	447
2.49900	0.01	455	455	454	454	454	454.4
2.49600	0.011	457	458	459	455	456	457
2.50000	0.005	450	453	451	454	452	451.2
2.49900	0.008	450	452	453	454	454	452.6
2.49820	0.007	456	458	455	454	455	455.6
2.50400	0.004	448	448	449	447	447	447.8
2.50920	0.005	445	446	446	445	444	445.2
2.50460	0.007	447	447	446	447	446	446.6
2.50000	0.005	450	450	451	451	451	450.6
2.51100	0.007	445	443	445	444	443	444



(Fig 5): *Relation between ball diameter of the indenter and hardness No (Ball 2.5mm 449HBW)*

(Table 10): *Effect of ball diameter on hardness No, Ball 2.5mm, 218.8±1 HBW*

Ball diameter mm	Range mm	HB1	HB2	HB3	HB4	HB5	Average HB
2.50240	**0.004**	**218**	**218**	**217**	**217**	**219**	**217.8**
2.50380	**0.003**	**217**	**218**	**217**	**217**	**218**	**217.4**
2.50100	**0.005**	**218**	**218**	**219**	**219**	**218**	**218.4**
2.50060	**0.009**	**219**	**219**	**218**	**219**	**219**	**218.8**
2.50340	**0.003**	**217**	**217**	**217**	**218**	**217**	**217.2**
2.49900	**0.01**	**222**	**219**	**220**	**222**	**222**	**221**
2.49600	**0.011**	**222**	**220**	**222**	**220**	**221**	**221**
2.50000	**0.005**	**218**	**220**	**220**	**218**	**219**	**219**
2.49900	**0.008**	**223**	**223**	**223**	**220**	**222**	**222.2**
2.49820	**0.007**	**221**	**221**	**222**	**221**	**222**	**221.4**
2.50400	**0.004**	**218**	**217**	**218**	**217**	**217**	**217.4**
2.50920	**0.005**	**217**	**217**	**215**	**216**	**215**	**216**
2.50460	**0.007**	**216**	**216**	**216**	**218**	**217**	**216.6**
2.50000	**0.005**	**218**	**218**	**219**	**218**	**219**	**218.4**
2.51100	**0.007**	**216**	**215**	**214**	**214**	**215**	**214.8**



(Fig 6): *Relation between ball diameter of the indenter and hardness No (Ball 2.5mm 218.8HBW)*

(Table 11): *Effect of ball diameter on hardness No, Ball 1mm, 450±1.5 HBW*

Ball diameter mm	Range mm	HB1	HB2	HB3	HB4	HB5	Average HB
1.0026	0.003	450	451	450	450	450	450.2
1.0034	0.014	451	449	449	452	451	450.4
1.0062	0.018	450	448	449	449	450	449.2
1.0016	0.011	447	446	446	446	447	446.4
1.005	0.003	449	449	448	448	448	448.4
0.998	0.007	454	453	453	453	453	453.2
0.997	0.012	454	454	453	454	455	454
1	0.004	456	457	456	458	455	456.4
1.001	0.006	455	454	454	453	454	454
0.988	0.005	459	458	458	459	458	458.4
1.011	0.006	448	447	447	446	447	447
1.009	0.007	448	449	447	448	448	448
1.012	0.008	447	448	448	448	447	447.6
1.017	0.002	446	446	447	445	445	445.8
1.007	0.005	449	449	450	448	449	449

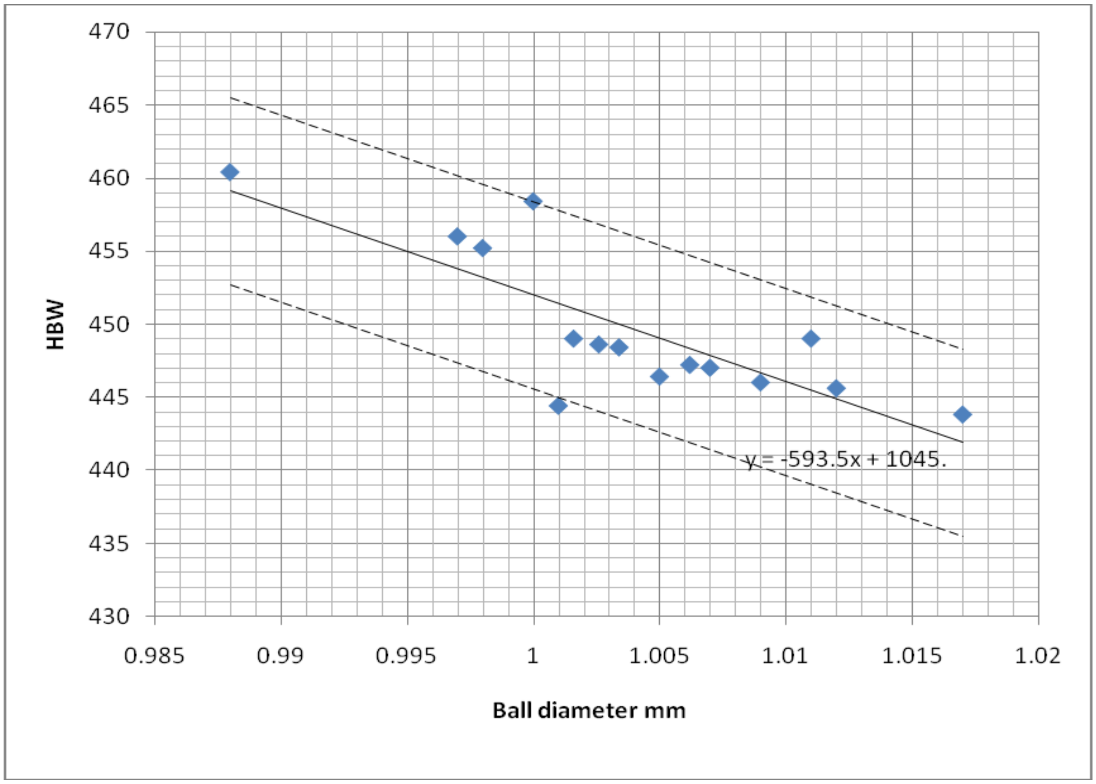
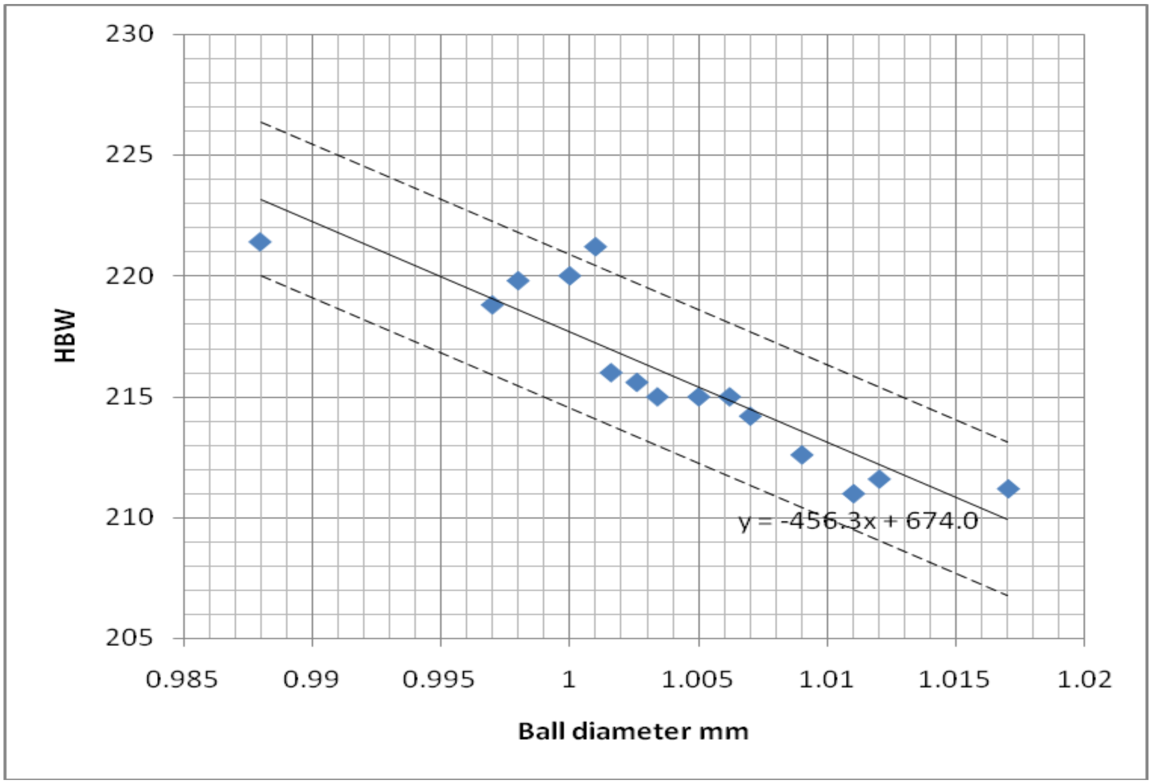


Fig 5 Relation between ball diameter of the indenter and hardness No, (Ball 1mm, 450 HBW)

***(Table 12)**: Effect of ball diameter on hardness No, Ball 1mm, 215.2±2 HBW*

Ball diameter mm	Range mm	HB1	HB2	HB3	HB4	HB5	Average HB
1.0032	0.003	215	216	215	216	216	215.6
1.0034	0.014	215	214	216	216	214	215
1.0062	0.018	214	215	215	216	215	215
1.0016	0.011	216	216	217	216	215	216
1.005	0.003	216	215	215	215	214	215
0.998	0.007	220	219	220	221	219	219.8
0.997	0.012	218	219	218	220	219	218.8
0.991	0.004	220	220	218	222	220	220
1.001	0.006	219	217	217	217	218	217.6
0.988	0.005	222	221	220	222	222	221.4
1.011	0.006	210	211	210	212	212	211
1.009	0.007	213	214	212	211	213	212.6
1.012	0.008	211	212	210	212	213	211.6
1.017	0.002	212	210	211	211	212	211.2
1.007	0.005	213	214	215	214	215	214.2



(Fig8): *Relation between ball diameter of the indenter and hardness No, (Ball 1mm, 215.2HBW)*

It is shown that the hardness value increases by the decreasing of the ball indenter diameter. Figure (3) shows that the diameter variation of 0.033 mm for the 5 mm ball nominal diameter leads to corresponding Brinell hardness variation 7 HB i.e. about 3.19% for the hardness value of 219 HB. This means that every 1 µm error in diameter of the ball gives a hardness error about 0.096%.; however, for balls of 2.5 mm nominal diameter, the hardness error is 3.4% for 0.015mm variation in ball diameter in the same hardness value (218.8 HB). It follows that every 1 µm error in diameter of the ball gives a hardness error about 0.23%. Furthermore, for balls 1 mm nominal diameter the hardness error is 4.83% for 0.029 mm variation in nominal diameter, i.e. each 1 µm error in diameter gives a hardness error of 0.17%.

For the specimens with the hardness value of 449 HB , also the balls with 2.5and 1 mm nominal diameter give hardness error higher than for 5mm. Balls 5 mm nominal diameter show for each 1 µm variation in diameter 0.068% hardness error, while for balls 2.5and 1mm the variation in corresponding Brinell hardness are 0.19%, 0.12% respectively.

It is shown that the standard error of estimate Se is about 0.4 HB for 5mm nominal diameters ball for the two hardness values, and for balls 2.5, and 1 mm nominal diameters are 1.5, and 3.2 HB respectively for 450 HB, and 0.9, 1.6 for 219 HB.

Estimated standard error as calculated from equation 2 gives an indication for the scattering of the results, which is mainly obtained from the roundness error.

Considering the balls No. 9 and 10 with diameters 2.499, 2.4998 mm, they have the max roundness error of 7.7and 7.2 µm respectively, and showed pronounced scattering in the results. In addition, for balls 1mm nominal diameter, the balls No. 8 and 9 with diameters 1 and 1.001 mm have the maximum roundness error of 7.8 and 8 µm respectively, and showed the same scattering in the results.

Considering the roundness error, it was shown from the results that the balls 2.5, 1 mm have roundness errors higher than the balls 5 mm nominal diameter, which resulted in increase in the standard error of estimate (Se) and the uncertainty values due to the scattering of the results . Figure 6-9 show that the balls with high roundness error values give higher scattering in results than the others.

4- Conclusion

The present study concerns with the effect of the ball indenter diameters and ball roundness error on the Brinell hardness value. It can be concluded that:

1- The measured hardness value increased with decreasing the ball indenter diameter. This implies overestimating the hardness value by using smaller indenters.

2- The balls with nominal diameter of 5 mm, 2.5 mm, and 1 mm , had diameter variation of 0.0334, 0.015, and 0.029 mm respectively , which leads to corresponding Brinell hardness variation of 3.19, 3.4, and 4.83% respectively for the reference hardness value of 219, and 2.2, 2.4, and 3.6% respectively for the 450 standard hardness value.

3- The balls with higher roundness error give high scattering in the results of the hardness test, which leads to a considerable effect on the uncertainty of the results.

4. The balls with nominal diameter of 2.499, 2.4998, and 1.001mm have max roundness errors of 7.7, 7.2, 7.8, 8 µm respectively, and they have significant scattering in results,

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