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EFFECT OF STEEL AND TUNGSTEN CARBIDE BALL INDENTERS ON ROCKWELL HARDNESS TESTS

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Abstract – Rockwell hardness (HR) is a valuable and widely used indentation hardness test for evaluating mechanical properties of metallic materials. For the Rockwell scales that use a ball indenter, either a steel or tungsten carbide (WC) ball indenter is permitted to be used in the test method standards of ASTM International and International Organization for Standardization (ISO). However, significant differences occur in Rockwell hardness tests depending on whether a steel or WC ball is used. In this paper, finite element analysis (FEA) is used to simulate the HR indentation process. The effects of four different sizes of steel and WC ball indenters on different Rockwell hardness scales are studied and compared with experimental measurements. This study provides important approximations of the differences between the performance of steel and WC Rockwell hardness indenters.

Keywords: Ball indenter, Finite Element Analysis, Rockwell hardness test

1. INTRODUCTION

Since Stanley P. Rockwell invented the Rockwell hardness test as a tool for obtaining a rapid and more accurate measurement of the hardness of ball races [1], the Rockwell hardness test has been expanded from the original Rockwell B hardness scale which uses a 1.588 mm (1/16 in.) diameter ball indenter, to other hardness scales employing different sizes of ball indenters and standard force levels. Today, the Rockwell hardness test has become the most widely used method for acceptance testing and process control of metals and metal products [2].

In older versions of the international standards of both ASTM International and the International Organization for Standardization (ISO), only steel ball indenters were allowed for Rockwell hardness (HR) tests. A common problem with steel ball indenters is the tendency of the balls to permanently flatten with use, which can result in erroneously elevated HR values. This flattening problem occurs to a much lesser degree for tungsten carbide balls. For that reason, the current Rockwell hardness test method standards, ASTM E 18-02 [3] and ISO 6508-1999 [4], allow the use of both steel and tungsten carbide (WC) ball indenters.

From the results of the Rockwell hardness tests performed at the National Institute of Standards and Technology (NIST) [5] and at commercial testing laboratories, it was found that there are measurable differences in the hardness measurement results when using ball indenters made of steel and tungsten carbide for the same test material and testing conditions. Ma et al. [6-7] studied the effect of deformable ball indenters on Rockwell B scale hardness tests using FEA simulation. The combined effect from both the ball and indented material deformation during the loading and unloading periods of Rockwell B scale hardness test were assessed. In this paper, the steel and WC ball HR differences are studied for all Rockwell ball indenter scales by both FEA simulation and experiments. The FEA simulation results show good agreement with the HR experiments.

2. ROCKWELL HARDNESS TESTS WITH BALL INDENTERS

The general Rockwell test procedure is the same regardless of the Rockwell scale or indenter being used. The indenter is brought into contact with the material to be tested, and a preliminary force is applied to the indenter. After holding the preliminary force for a specified time period, the depth of indentation is measured as h(loading). An additional amount of force is then applied at a specified rate to achieve the total force, which is held constant for a specified time. The additional force is then removed, returning to the preliminary force level. After holding the preliminary force constant for a specified time period, the depth of indentation, h(unloading), is measured for a second time, followed by removal of the indenter from the test material. The measured difference between the first and second indentation depth measurements, h, is then used to calculate the Rockwell hardness number [2].

Many manufactured products are made of different types of metals and alloys varying in hardness, size and thickness. To accommodate the testing of these diverse products, four different diameters of ball indenters were developed for the Rockwell test to be used in conjunction with a range of standard force levels. Each combination of ball indenter size and applied force levels has been designed as a distinct Rockwell hardness scale, as shown in Table 1. Rockwell hardness scales are divided into two categories: regular Rockwell scales and superficial Rockwell scales. Both categories of tests use the same types of indenters. The regular Rockwell scales employ the heavier force levels.

The superficial Rockwell scales employ lighter force levels, typically for use on thinner materials. The Rockwell hardness number is calculated for ball indenter scales as:

$$Regular\ Rockwell\ Hardness = 130 - \frac{\Delta h}{0.002} \quad (1)$$

$$Rockwell\ Superficial\ Hardness = 100 - \frac{\Delta h}{0.001} \quad (2)$$

where $\Delta h = h(\text{unloading}) - h(\text{loading})$ in mm.

TABLE I. Rockwell hardness scales with the corresponding ball indenter diameter and applied forces

Ball Indenter Diameter		Scale Symbol	Preliminary Force N (kgf)	Total Force N (kgf)		Scale Symbol	Preliminary Force N (kgf)	Total Force N (kgf)
1.588 mm (1/16 in.)	Regular Rockwell Scales	F	98.07 (10)	588.4 (60)	Superficial Rockwell Scales	15T	29.42 (3)	147.1 (15)
		B		980.7 (100)		30T		294.2 (30)
		G		1471 (150)		45T		441.3 (45)
3.175 mm (1/8 in.)		H		588.4 (60)		15W		147.1 (15)
		E		980.7 (100)		30W		294.2 (30)
		K		1471 (150)		45W		441.3 (45)
6.350 mm (1/4 in.)		L		588.4 (60)		15X		147.1 (15)
		M		980.7 (100)		30X		294.2 (30)
		P		1471 (150)		45X		441.3 (45)
12.70 mm (1/2 in.)		R		588.4 (60)		15Y		147.1 (15)
		S		980.7 (100)		30Y		294.2 (30)
		V		1471 (150)		45Y		441.3 (45)

3. EFFECT OF STEEL AND WC BALL INDENTERS ON ROCKWELL HARDNESS TESTS

The effect of steel and WC ball indenters on all Rockwell ball indenter tests was studied by both FEA simulation and experiments. For the FEA modeling, to take advantage of axis-symmetry, only a cross section of a half ball was modeled. The plastic deformation was modeled by the J_2 flow plasticity theory with isotropic hardening. For the detailed modeling process, please see reference [6, 7]. For different ball sizes, the same type of mesh was selected with the element size being slightly different. Performance comparisons of steel and WC Rockwell hardness indenter balls from the FEA simulation and experiments are shown in Figs. 1 through 4 for four different diameters of ball indenters.

The NIST experiments, shown in Figs. 1 through 4 as solid diamonds, were conducted using a commercial Rockwell hardness machine. For most of the experimental testing, three brass reference blocks were selected with nominal hardness levels of 42, 62 and 82 HRB. A steel reference block was used for the higher hardness HRG tests and an aluminium alloy reference block was used for the highest hardness levels of some HR scales. A common indenter ball holder was used when testing with both steel and WC balls. The HR values were measured with both a steel and WC ball using the same testing cycle. Because the FEA model neglected the creep during a HR measurement, the NIST experimental test cycle dwell times were minimized to 0.1 s. For each ball indenter, three test positions were selected evenly distributed on the block's surface. The test locations using the WC indenter were chosen adjacent to those of the steel ball indenter, so that the HR difference mainly reflected the difference of these two indenters, rather than the hardness non-uniformity of the reference block. The experiments of the commercial Labs 1, 2, 3 and 4, as shown in Figs. 1 through 4, were made on their own reference blocks using their own commercial Rockwell hardness machines with their own common ball holders for the same size of WC and steel balls. The testing cycle used by each laboratory was not reported and the number of measurements varied from three to five. For each set of HR test readings, their mean HR value was calculated*. The data are shown in Figs. 1 through 4 as the difference between the mean values of the test results of the steel and WC ball indenters. The apparent HR with the steel ball is always greater than HR with the WC ball.

As reported in our former research [6,7], indentation depth h, for both h(loading) and h(unloading), is comprised of both indenter ball deformation and indented material deformation. The ball deforms more when testing harder materials. This is because the indenter-specimen contact area decreases for harder materials under the same indention load. Consequently, the relative specimen indention depth, which is the relative indention depth due to the material deformation using a steel or WC ball as compared with a rigid ball, is not simply an increasing or decreasing function of the material hardness, since it is determined by both the specimen material hardness and the changing shape of the indenter balls during loading and unloading.

3.1. HR difference for the same Rockwell scale

From Figs. 1 through 4, it can be seen that for the same Rockwell scale, or the same size of ball indenter and load levels, the hardness differences between steel and WC balls are not constant for different hard and soft materials because of the combined effect from both the different ball materials and the different hardness levels of test block materials during the loading and unloading periods, as described in our former research [6, 7]. For some HR scales, such as HRB shown in Fig. 1a, the data from different laboratories is widely varied, which is likely due to typically large hardness non-uniformity in brass and aluminium reference blocks, as well as the use of different testing cycles.

3.2 HR difference for different total force levels with the same size of ball indenters

To study the effect of the total force on the HR difference between measurements using steel and WC ball indenters, we individually compared the results of each set of three Rockwell hardness scales that use the same preliminary force and indenter ball size. For example, the HRF, HRB and HRG scales use the same preliminary force of 98.07 N and the same ball size of 1.588 mm with different total forces of 588.4 N, 980.7 N and 1471 N,

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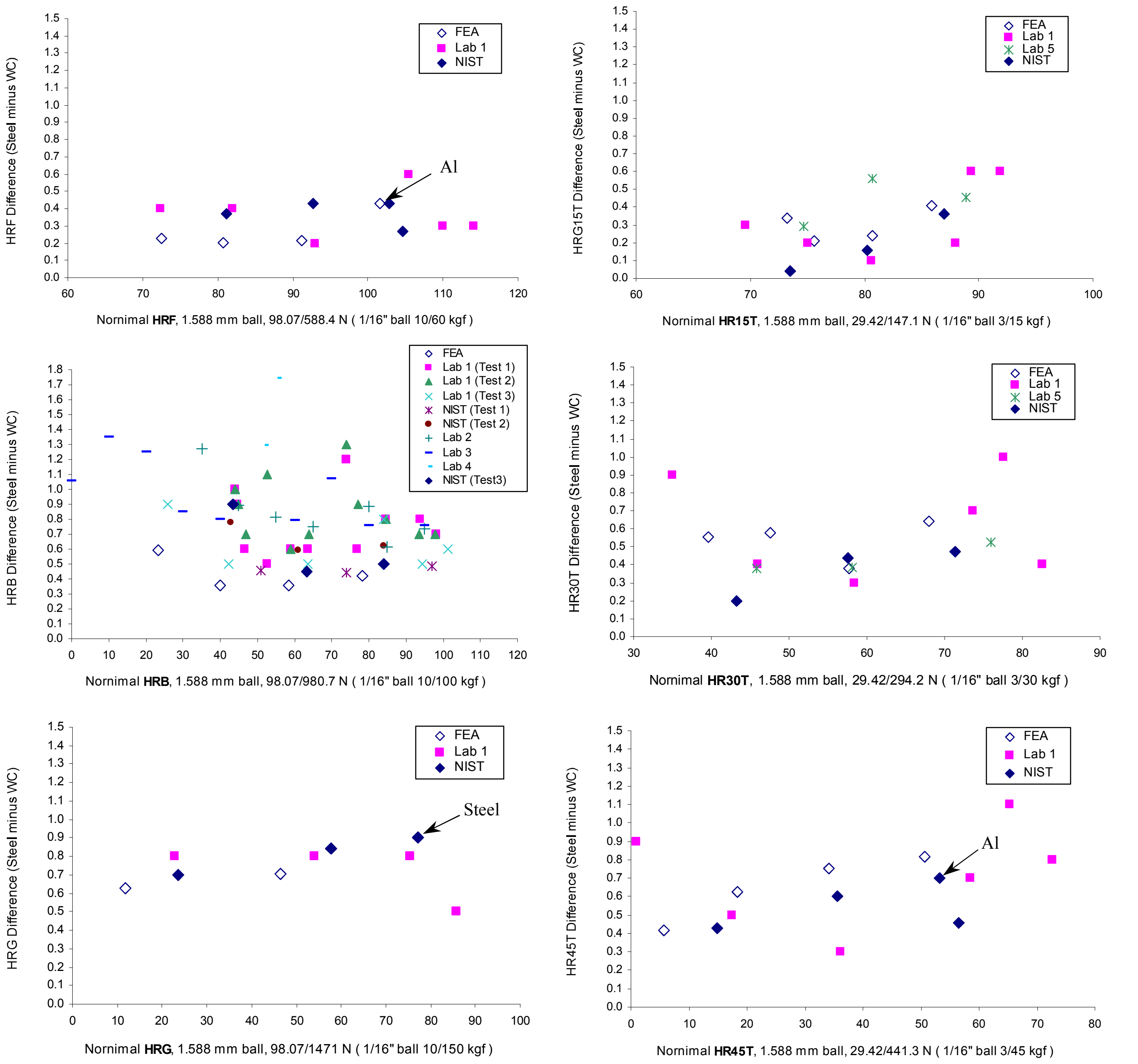
* The combined uncertainty u_c (k=1) of the hardness differences, plotted in Figs. 1 through 4, for the NIST measurements does not exceed 0.31 except for the lowest hardness HRG block which is approximately 0.65 HRG calculated as $u_c = \sqrt{\sigma_{Steel}^2 + \sigma_{WC}^2 + \left(r/\sqrt{12}\right)^2}$ where σ_{Steel} is the standard deviation of the measurements using a steel ball, σ_{WC} is the standard deviation of the measurements using a tungsten carbide ball, and $r = 0.1$ is the display resolution of the hardness tester. The uncertainty of the measurements made by the other laboratories is unknown.

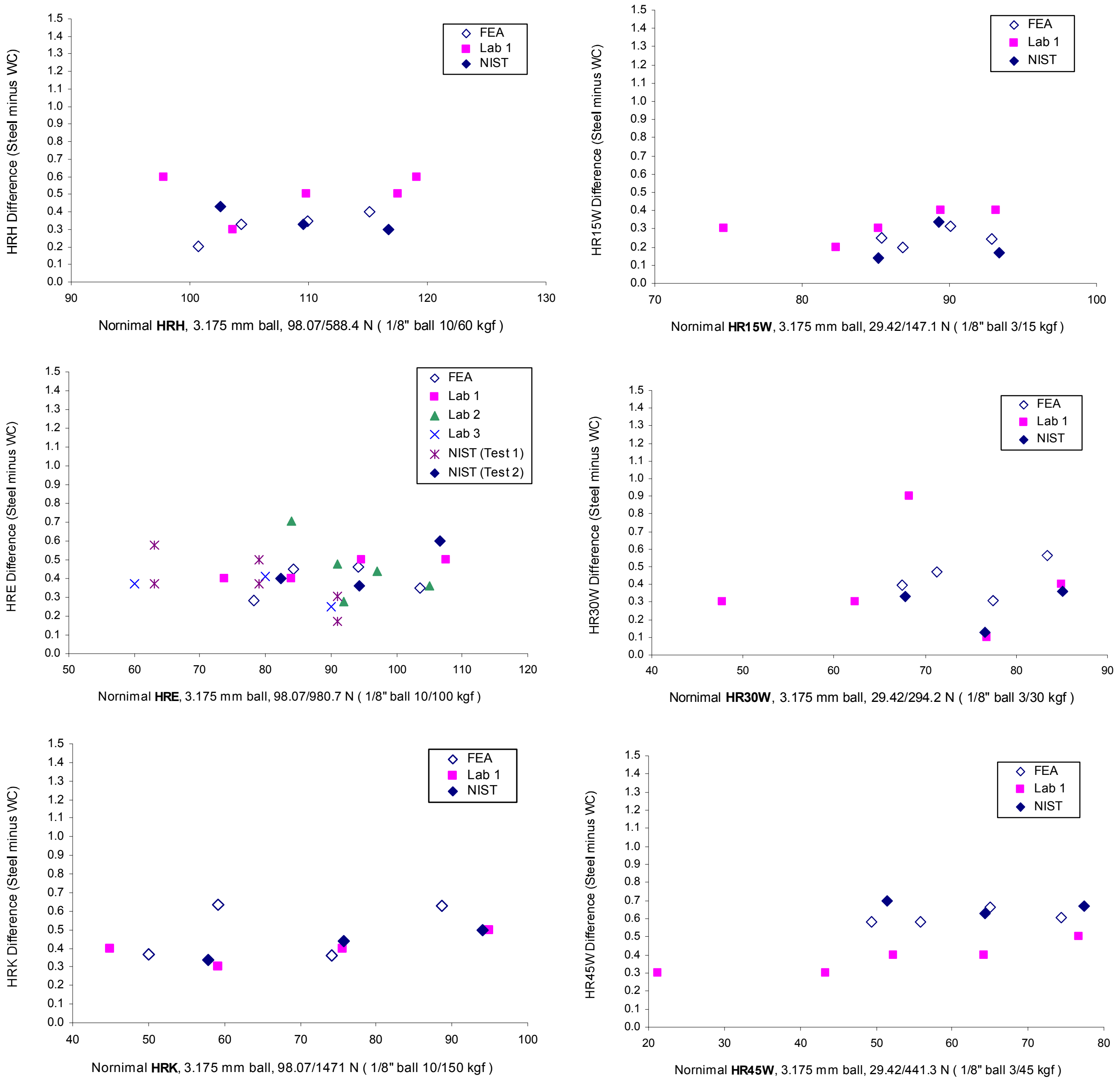
respectively. Due to having the same preliminary force, the indentation depth differences during preliminary force loading are constant. Therefore, variations in the HR differences between the three HR scales are due to the indentation depth differences measured following the removal of the additional force while under the preliminary force.

Figure 5 shows the FEA simulation results of differences between steel and WC ball indenters in the amount of ball compression that occurs while under the total force (Fig. 5a), and following the removal of the additional force while under the preliminary force (Fig. 5b). Keep in mind that the compression of the ball contributes to the apparent indentation depth measured by a Rockwell hardness machine. The ball compression is plotted as a function of the total force level of the HR scales. It can be seen that, while under the total force, for the HR scales using the higher total force levels, there is a larger difference between the amount of ball compression that occurs for the same size of steel and WC balls (see Fig. 5a). Conversely, while under the preliminary force (following the removal of the additional force), for the HR scales using the higher total force levels, there is less difference between the amounts of ball compression that occurs (see Fig. 5b, upper data lines). This is because for the same size of ball, as the force is increased during a Rockwell test, the contact pressure increases which increases the ball deformation by an amount dependent on the modulus of the ball material, and



(a) (b)

Fig. 1. FEA and performance comparison of steel and WC Rockwell hardness indenter balls of 1.588 mm (1/16 in) diameter for (a) regular and (b) superficial Rockwell scale. (Brass reference blocks were used for the experiments except the ones indicated in the figure)



(a) (b)

Fig. 2. FEA and performance comparison of steel and WC Rockwell hardness indenter ball of 3.175 mm (1/8 in) diameter for (a) regular and (b) superficial Rockwell scale.

therefore the difference in the amount of deformation in the two types of balls also increases. The higher the total force applied, the higher the plastic strain in the specimen, as well as, the higher the residual deformation left in the specimen. So, following the removal of the additional force and returning to the preliminary force, for the HR scales employing the higher total forces, the contact area is larger and the contact pressure is reduced, which decreases the ball deformation also by an amount dependent on the modulus of the ball material. Therefore, in contrast to the effect while under the total force, the ball deformation difference becomes smaller while under the preliminary force.

Shown in Fig. 5b is an example of the varying relationship of the indentation depth difference for the indented material only (bottom data lines), excludes depth due to ball compression (top data lines), as a function of the increasing total force levels of the HR scales. Interestingly, the depth difference does not simply increase or decrease with increasing total force levels, but instead is variable as a function of the increasing total force, but the variation is different depending on the sets of Rockwell scales compared. This is due to the complicated combined effect of both the hardness of the indented material and the depth difference due to the total force difference affecting the changing shape of the indenter balls. Thus, the total indentation depth difference (see Fig. 5b, central lines), which is the sum of the ball deformation difference and the depth difference for the indented material, also is not simply an increasing or decreasing function of the total forces levels of the HR scales. Although this data indicates that, following the removal of the additional force and returning to the preliminary force, the depth of the steel ball is sometimes greater than the depth of the WC ball as well as sometimes the reverse, the final hardness values made with a steel ball are always higher than when using a WC ball. This is because the magnitude of the total depth difference during the initial preliminary force is always greater than the depth difference following the removal of the additional force and returning to the preliminary force (a steel ball always exhibits the greater apparent depth primary due to higher ball compression then a WC ball, which the machine interprets as part of indentation depth). As a result, the steel ball tests exhibit a smaller value of h (see equations 1 and 2), and, consequently, a higher hardness value than when using a WC ball.

3.3 HR difference for the same total force level with different ball indenter size

From Fig. 5, it can be seen that for the same force levels, when the ball size is increased, the ball deformation difference decreases since the contact area increases which decreases the deformation. However, we observed that for different hardness levels of test materials, there is no

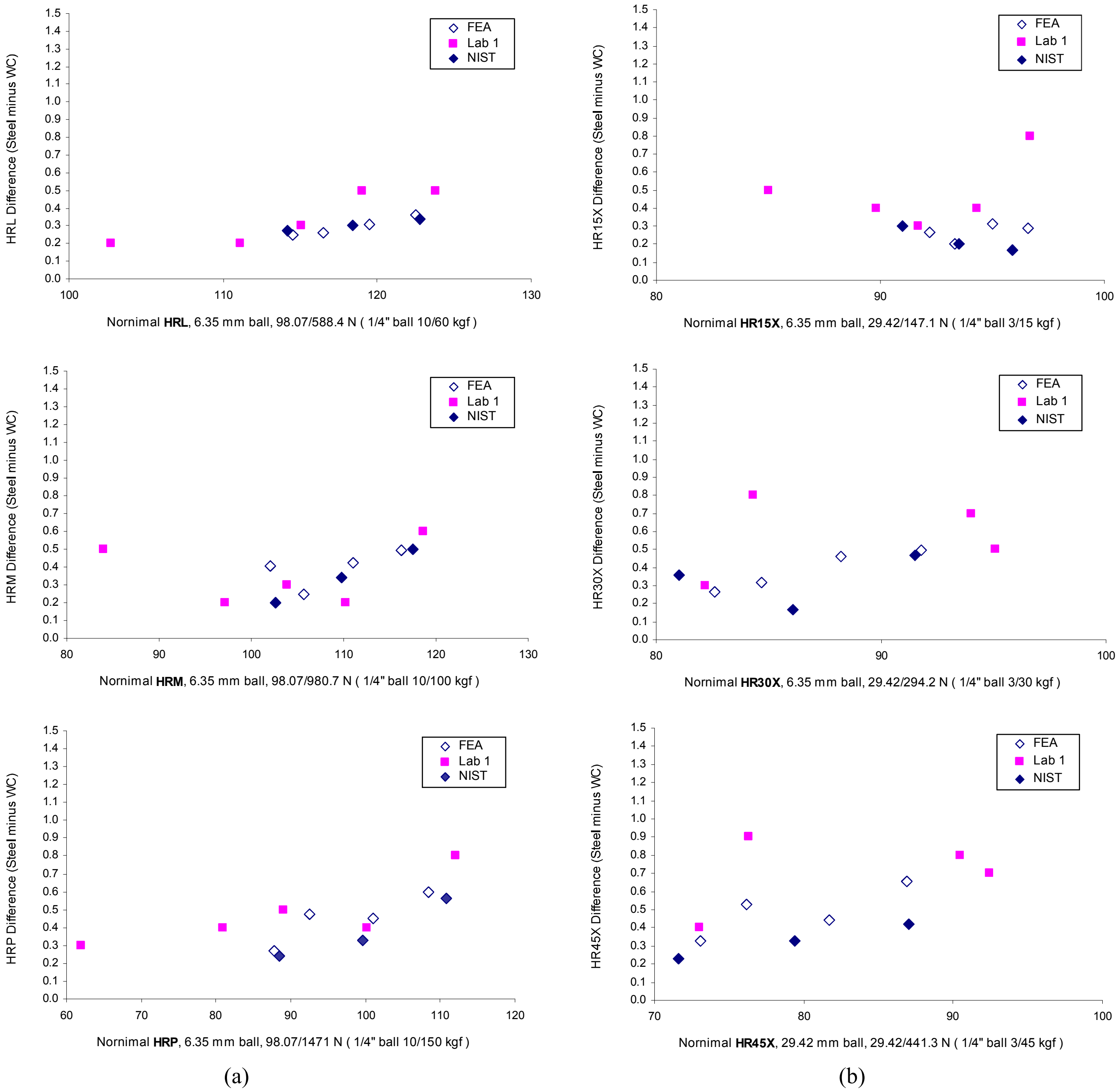


Fig. 3. FEA and performance comparison of steel and WC Rockwell hardness indenter ball of 6.35 mm (1/4 in) diameter for (a) regular and (b) superficial Rockwell scale.

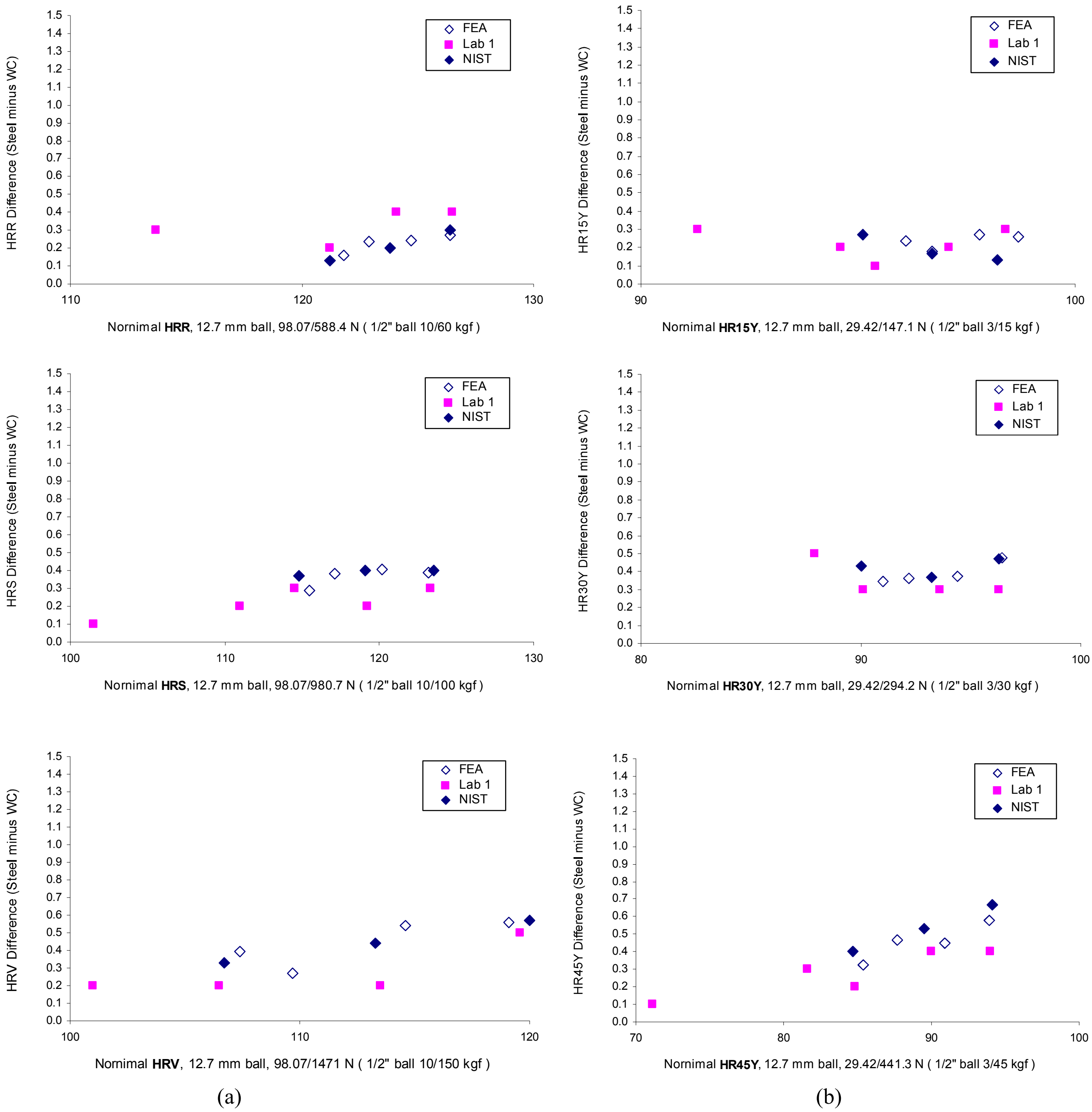
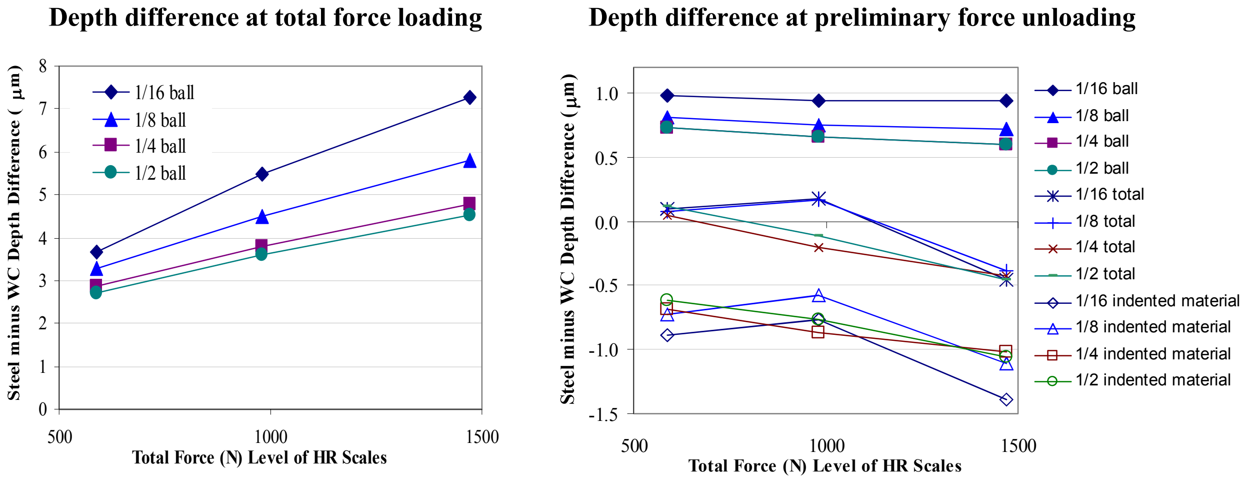


Fig. 4. FEA and performance comparison of steel and WC Rockwell hardness indenter ball of 12.7 mm (1/2 in) diameter for (a) regular and (b) superficial Rockwell scale.

obvious trend for the depth difference for the indented materials due to the combined effect of both the indented material hardness and the depth difference due to the size of the ball affecting the changing shape of indenter balls.

4. CONCLUSION

In this paper, finite element analysis is used to simulate the Rockwell hardness test and analyze the effect of steel and WC ball indenters on the measurement values. The influence of the deformation of the ball indenter and specimen is studied and assessed for different indented material hardness levels, ball sizes and force levels during the loading and unloading. Because of a combined effect from both the ball deformation and indented materials deformation during the loading and unloading periods, it has been found that the HR differences between steel and WC balls is not a simple function of either the total force level, ball size, or hardness level within a single HR scale. This is particularly true for HR differences with respect to increasing hardness levels within the same HR scale, where we observed that in some cases the differences increased, in some cases decreased and in some cases was not a simple increasing or decreasing function. In the case of comparing different HR scales using the same ball size, although the relationship between HR differences and total force level



(a) (b)

Fig. 5. Depth difference between steel and WC ball with the change of total force level of HR scales for difference ball sizes at (a) total force loading and (b) preliminary force unloading of the indented Al 2024-T6 material from FEA modelling (The number labels in the legend represent the ball diameter in historical inch units)

is also not a simple increasing or decreasing function, the general trend was found to be an increase in the HR differences for the HR scales using the higher total force levels. In the case of comparing the effect of different ball sizes, even though there is similarly not a simple increasing or decreasing relationship, the general trend was found to be a decrease in the HR differences with increasing ball size, which is obvious for 1.588 mm and 6.35 mm diameter ball indenters but diminishes for the larger ball sizes. The FEA simulation results agree with the experimental results.

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