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Effect of Selected Conditions of Hardness Tests on the Accuracy of Measurements

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Abstract **- The research includes a study for different selected conditions of hardness tests and their effects on accuracy of measurements. These hardness tests include Rockwell hardness test (HRC), Rockwell hardness test (HRB), Vickers hardness test (Hv) & Brinell hardness test (HB). The research include study the effects of different conditions and effects as analysis of hardness measurements, use of hardness conversion table, types of applied load, indentation method, test environment and calibration on accuracy of hardness measurements so for these reasons a different heat treatments are applied for two groups of steel specimens (low and high carbon steel) therefore a wide range of hardness measurements have been taken in this research which represent measurements of hardness tests for different heat treated steel specimens .It was noticed from the results that heat treatments influence n hardness number of both steels and the non-equilibrium conditions of heat treatment influence strongly on hardness of steel. Also selection the type of hardness test will influence on the accuracy of hardness measurements which depend largely on tester experience and type of alloy to be tested .Also hardness test that depend on depth of indentation give higher accuracy as compared with those tests that depends on area of indentation that occurs on surface of specimen due to applied of test load.**

Keywords: Hardness, Steels, Accuracy, Test.

I. INTRODUCTION

Mechanical properties are considered the distinctive properties of metals and alloys which provide engineer and designer with data necessary to separates between successes of design from its failure, so mechanical properties can be classified basically according to the type of load applied on the part. The applied load may be a static load, a dynamic load, or an impact load. Hardness is consider one of the important mechanical properties which is defined as resistance of material to abrasion [1] also it can be defined as a measure of the material's resistance to localized plastic deformation [2] so hardness is consider a major interest mechanical property for metallurgists because it can explain the condition of alloy in terms of its ability to withstand the applied loads and abrasion. Accordingly, the tests of hardness is varied and many ideas were generated by experts and specialists in this field to achieve the maximum possible benefit since the result of the test will be the decisive factor in the success or failure of the mechanical product which goes through a series of technological processes in workshops to reach the desired final product, by the way it is better for engineers to know the hardness value of the raw material to be used in production before beginning of manufacturing processes in order to avoid losses and waste of material energies in the work.

Another importance of hardness test in matching the mechanical properties of the product to design conditions, as the required hardness value for the product is usually fixed at design layout in addition to the type of alloy chosen. The famous type used in hardness test is Rockwell hardness test, Brinell hardness test and Vickers hardness test. These tests are depend in working principle on the ability to penetrate an indentor made of a specific material, such as diamond or hardened steel, into the depth of the surface of the metal part for a short period of time so the metal resist the load applied by indentor, then hardness will be taken from the equipment directly or calculated by an equation. The indenter will cause a pit of a specific shape on the tested surface of a metallic specimen, and certainly the hardness value is directly proportional to the area of pit obtained so a larger the pit, the lower the hardness value. Some tests are depends in their principle on the area of the impression or pits produced on the tested surface, other are depends on the depth of the impression only not its area. The tests methods that depend on the area of the pit are Brinell and Vickers tests while the method that depends on the depth of the resulting pit is the Rockwell tests and using. Also using of Vickers test with applied loads of values less than one kilogram will transform the Vickers scale into what is known as a micro hardness test which has great benefits in checking the hardness of some products especially metals coated with layers.

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II. METHODOLOGY

Different heat treatments were applied on steel specimens. Two types of steels were selected for this purpose; these are low carbon steel and high carbon steel. Electrical furnace up to 1200ºC is used for the heat treatments which include equilibrium and non-equilibrium treatments. Equilibrium treatments are the annealing process and normalizing process were applied on both steels but non equilibrium heat treatments. i.e. water quench with tempering and oil quench with tempering were applied on high carbon steel only. Brooks hardness equipment is used to measure the hardness of specimens after make the heat treatments.

III. RESULTS AND DISCUSSION

Table (1) represents measurements of hardness for all specimens. The letter (H) refers to high carbon steel specimens and the letter (L) refers to low carbon steel specimens.

Table 1: Hardness measurements of specimens

Specimen no.	Condition	Hardness
1	steel (H. water quenched and tempered at 200ºC).	60 HRC
2	steel (H. water quenched and tempered at 350ºC).	50HRC
3	steel (H. oil quenched).	40 HRC
4	steel (H. normalized).	25 HRC
5	steel (H. annealed).	95 HRB
6	steel(L. normalized).	80 HRB
7	steel(L. annealed).	52 HRB

The discussion and analysis in this research include many factors, these are analysis of hardness measurements , effect of use of conversion table on accuracy of measurement, effect of types of load on accuracy of measurement, effect of indentation method on accuracy of measurement , effect of environment and effect of calibration on accuracy of measurement.

1. Analysis of hardness measurements

Figure 1 represents hardness measurements for specimens (1,2,3&4) and figure2 represent measurement of hardness for specimens (5,6&7). It was noticed from these figures that there is a variation between hardness measurements for all specimens.

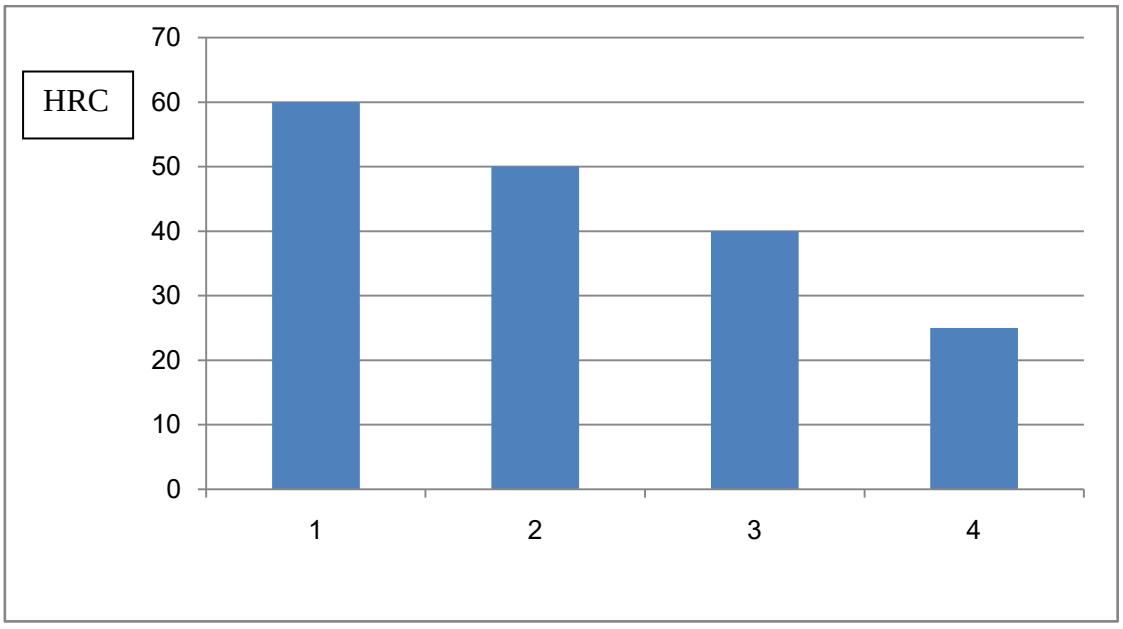

Figure 1: Hardness measurements for specimens (1,2,3&4)

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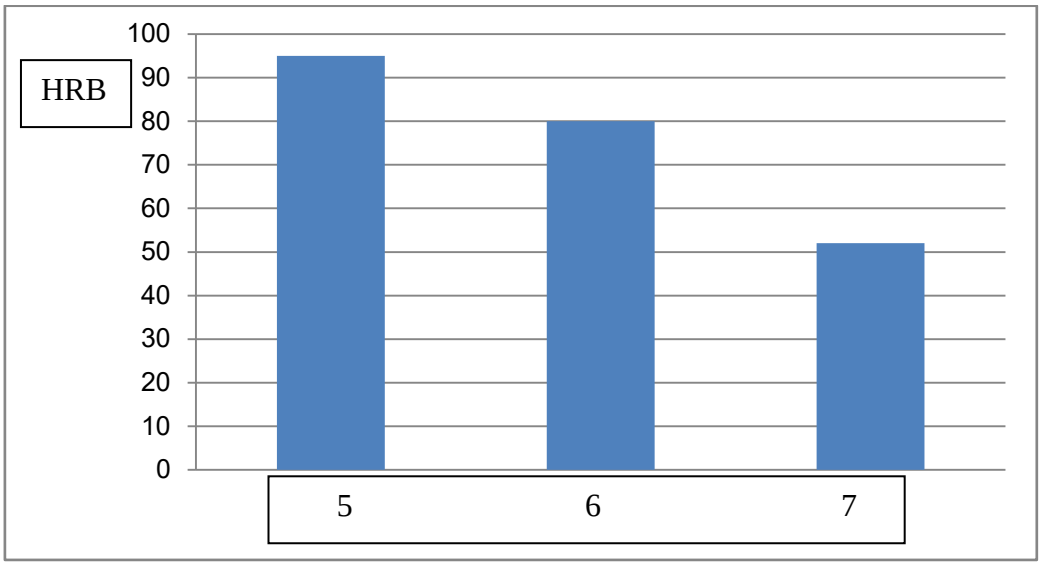

Figure 2: Hardness measurements for specimens (5,6&7)

This variation is due to different conditions used in heat treatment. also there is a clear difference between hardness of the two types of steels (H & L) and this is because high carbon steel (H) is consider as a heat-treatable steel, while low carbon steel (L) is consider as non-hard enable steel [3]. i.e. non equilibrium heat treatments (water quench-oil quench) influence on hardness obtained of high carbon steel only but equilibrium heat treatment (annealing, normalizing)is useful for two types of steels [4]. At this point, the selection of heat treatment type is often depending on what is known as the time-transformation-temperature curve which explain possibility of phase transformation to occur [1]. Figure (3) show this type of diagrams.

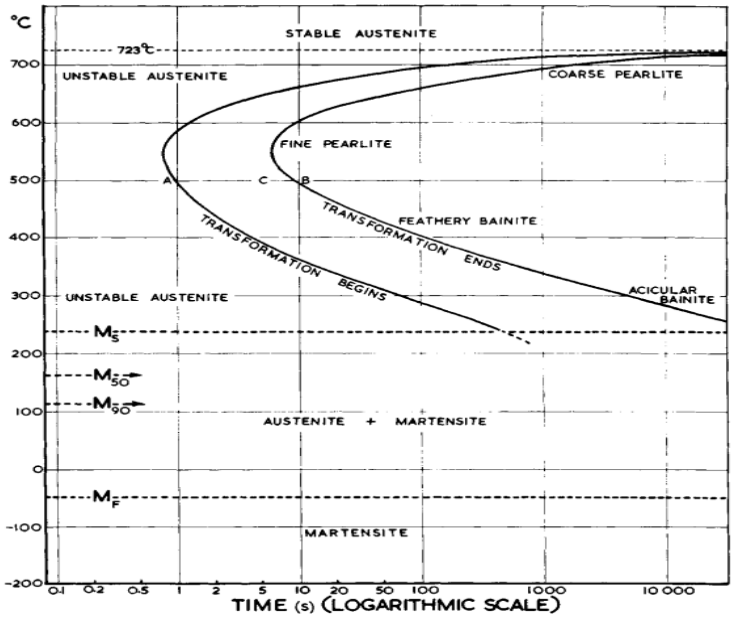

Figure 3: Time-temp.-transformation of steel [1]

It was noticed from hardness measurements that water-quenched specimens obtain a high hardness values as compared to other specimens and specimens of high carbon steels specimens (no.1 to no.5) has a greater values of hardness as compared to low carbon steels specimens (no.6 & no.7). This can be explained according to the value of critical cooling rate of time –temperature-transformation diagram (Figure1) which is equal to about ten seconds for low-carbon steel and sixty seconds for high carbon steel [1] and this gave high carbon steel the possibility of phase transformation and gaining greater hardness values as compared with low carbon steel and this is the reasons of high hardness values which obtained for the water-quenched specimens compared to

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other specimens which are cooled by other cooling mediums. Hence, it must be confirm that heat treatments are considered very important process in the stages of the production processes in workshops because most steel products, such as engine parts are heat-treated to obtain the required mechanical properties.

2. Effect of use of conversion table

In order to compare results of hardness tests and use it among specialists, a conversion table is usually used to compare between the hardness values. This table is suitable for steels in accordance with international standard specifications [5]. Table (2) represents conversion of hardness values. It was noticed from this table that there is a possibility to convert the hardness number to other scales like HB and Hv [5,6].

Table 2: Conversion table of hardness values

Specimen no.	Hardness (measure)	HV(by conversion table)	HRB(by conversion table)	HB(by conversion table)
1	60 HRC	700	------	----
2	50 HRC	520	----	494
3	40 HRC	400	----	380
4	25 HRC	270	----	237
5	95 HRB	220	95	209
6	80 HRB	155	80	147
7	52 HRB	95	52	90

Based on table no. (2), a graphical relationship between these scales was plotted. i.e. Rockwell hardness, Brinell hardness and Vickers hardness results were drawn versus each other. It was noticed from these graphs that relationship is consider as a first degree, with deviation in the slope of the line, as shown in Figure 4.

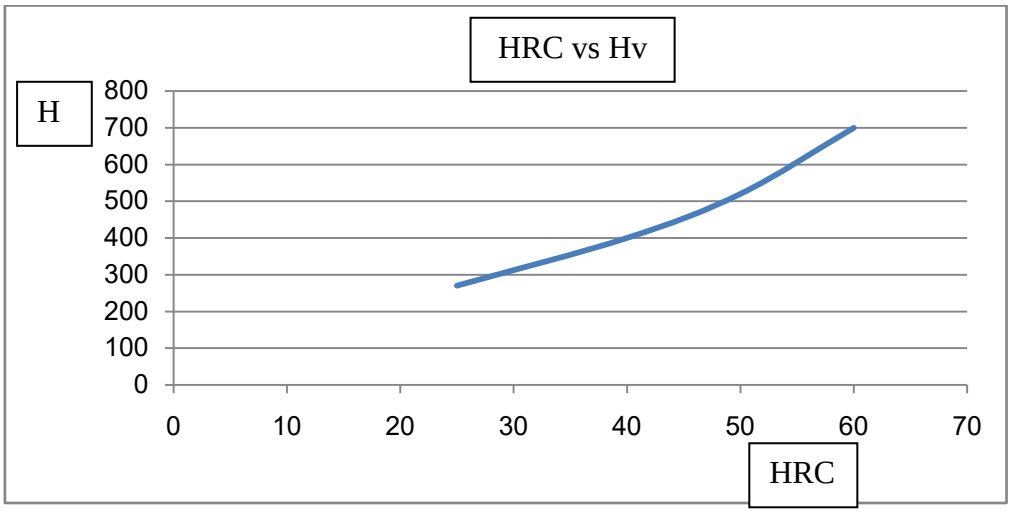

Figure 4: Relation between HRC and Hv for specimens (1,2,3&4)

For the specimens (5,6&7), the relationship between HRB and Hv by using conversion table, we also notice from figure 5 that relation represent a first-order relationship with a deviation in the slope of the line.

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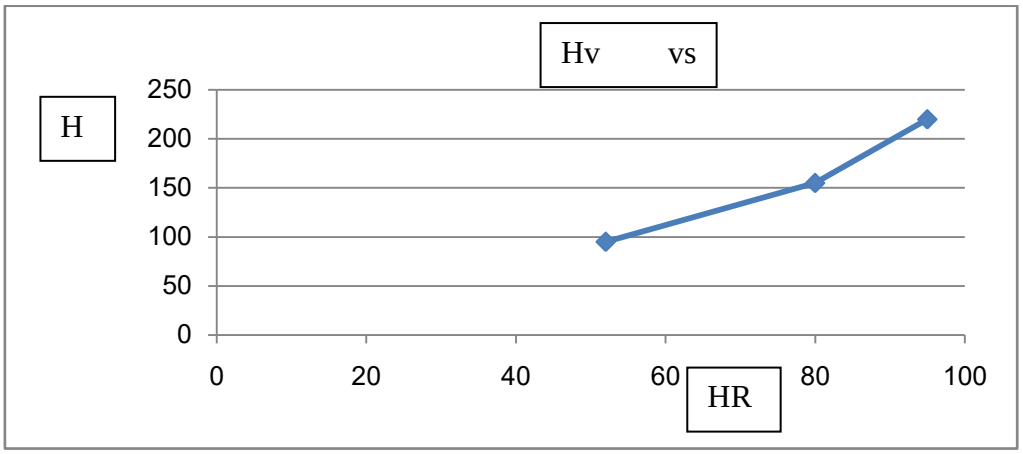

Figure 5: Relation between HRB and Hv for specimens (5,6&7)

Now if we draw the relation between HRC vs HB for specimens (1,2,3&4)as in figure6 we can see also the first degree relation between them but with a deviation in the slope.

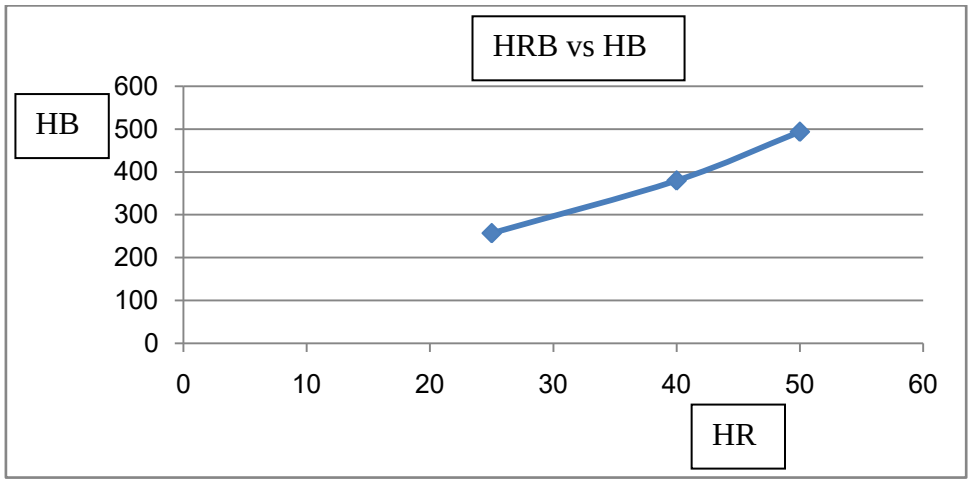

Figure 6: Relation between HB and HRC for specimens (1,2,3&4)

The same concept explains the relation between HRB and HB as in figure7 below.

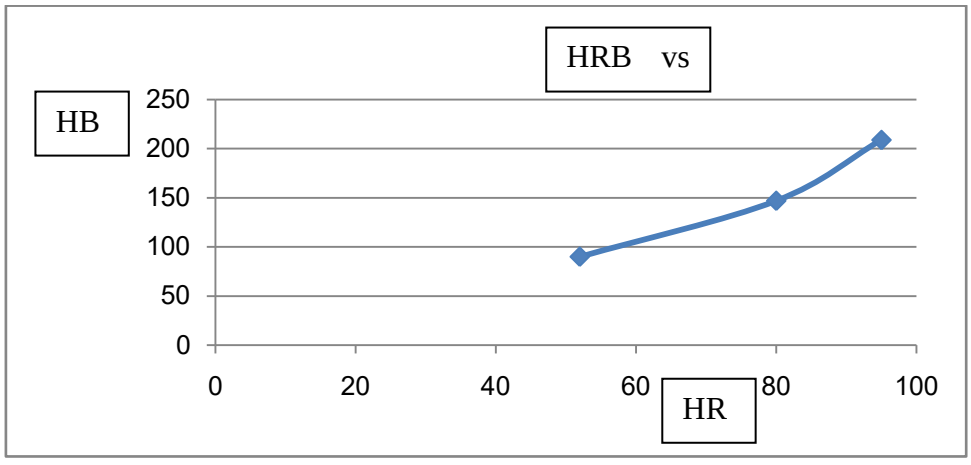

Figure 7: Relation between HRB and HB for specimens (5,6&7)

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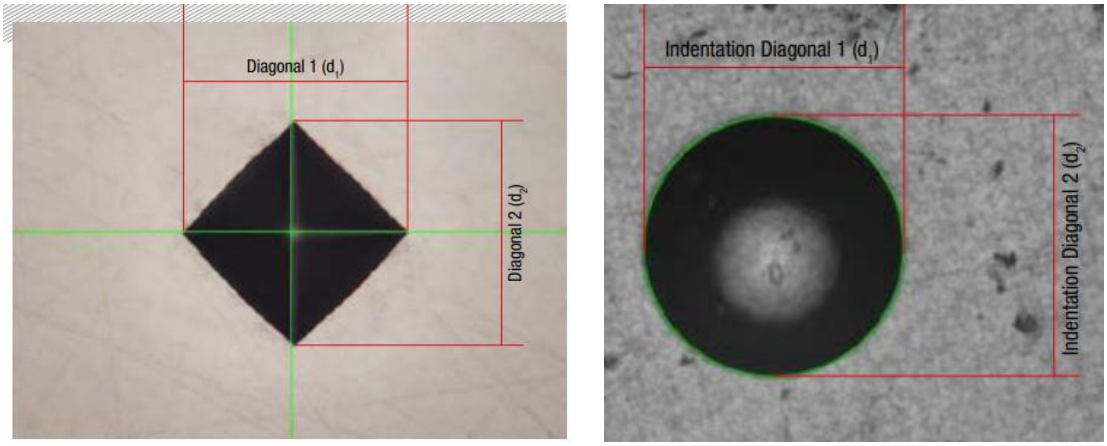
From the figures 4 to 7 one can notice that the deviation is present at all figure and this is due the conversion between hardness values. i.e conversion table give an estimation only between hardness types.

3. Effect of load in Brinell, Vickers and Rockwell tests

Measurements of Vickers and Brinell hardness methods are depend on the area of the pit resulting from apply of load and these devices are usually equipped with a magnifying lens with a specific magnification power (often 140 X magnification) [7] so this lenses will magnify the pit resulting for the purpose of measuring the area of indentation by the tester then using it in the mathematical equation related to the Brinell or Vickers tests. The equation depends in its principle on the value of the applied load divided by the area of the pit resulting from the test

$$H = \frac{Load\ P}{surface\ area\ of\ indentation A} \qquad [1]$$

From the above equation it is clear that value of the applied load, as well as the pit area, specifically in the Brinell and Vickers methods have a very influence on the test result, as the load is directly proportional to the resulting hardness value. If the applied load is not selected accurately, this will lead to deformation the shape of the pit resulting from the hardness test which leads to difficulty in determining the value of the area, which will give an inaccurate test result. Another factor must be taken in account when using Brinell test , this is the diameter selection of the steel ball (indentor) which is used in the test as a penetration tool, otherwise a distortion will also occur in the shape of the pit resulting from the test, which negatively affects the result of the hardness test but in Vickers test this is not happen because the choice of the applied load is available according to the experience of the tester until the correct shape of the pit is reached, so, there is no effective ratio between the applied load and the penetration tool here. The following figures show the method of calculating the indentation areas in Vickers and Brinell hardness tests by calculating the resulting area.



(a) **(b)**

Figure 8: Images of indentation for Vickers (a) and Brinell hardness tests (b) [9]

In order to obtain a good accurate result, the lowest possible load should be chosen when examining the Vickers and the resulting effect should be monitored due to the implantation of the penetration tool on the surface of the metal model. If the effect does not appear clear or has a small area, the examination must be repeated and the location of the new penetration changed, and so on, until a clear effect whose dimensions can be measured is obtained.

As for the Brinell test, a pit must be obtained in the form of a regular circle with a clear center and a similar diameter, while in the Vickers test, a regular rhombus must be obtained with two regular diameters, preferably equal, in order to take the average of the two diameters as in figure 6 and enter it into the following mathematical equation:

$$HB = \frac{2P}{\pi D[D - \sqrt{D^2 - d^2}]} \qquad [2]$$

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$$HB = \frac{2P}{\pi D[D - \sqrt{D^2 - d^2}]} \quad [3]$$

Here comes the experience of the examiner in how to choose the applied load in the two methods of examining the Brinell and Vickers hardness. If the examiner is a beginner or has little experience, he should use the information booklet attached to the device to show him the relationship between the load and the diameter of the Brinell penetration tool, while the Vickers still needs the experience of the examiner. For example, the Brinell hardness examination can be performed by choosing a fixed load with a specific diameter of the penetrating tool (steel ball) and staying away from magnifying lenses. The same procedure applies to the Vickers examination, which relies on a fixed, pyramid-shaped penetrating tool with the highest load chosen. To treat such scientific problems that may occur in the work environment, manufacturers have made modifications to the hardness testing devices, and have manufactured a universal hardness equipment but it was noticed that this device does not give the required accuracy in the hardness tests.

In Rockwell tests, which consists of several secondary types, as shown in the following table.

Table 3: Types on indenters used I Rockwell test

Scale	*Indenter*	*Total force (kgf)*
A	Diamond cone	60
B	1/16″ steel ball	100
C	Diamond cone	150
D	Diamond cone	100
E	1/8″ steel ball	100
F	1/16″ steel ball	60
G	1/16″ steel ball	150
H	1/8″ steel ball	60
K	1/8″ steel ball	150

[4]

It is noted from Rockwell's tests that the value of the load applied during the test is consider constant. The test does not depend on the area of the pit resulting from the test, but rather depends on the depth of the resulting pit in the metal surface [10], which does not require the presence of a magnifying glass so will give some benefits as importance of the quality of the tester vision is less compared to the Brinell and Vickers tests, and with every benefit there are disadvantages. For example, the hardness of the paint layer cannot be measured by the Rockwell method, but rather the Vickers method must be used with loads less than one kilogram what is known as microhardness test due to the possibility of controlling the applied load. Also Current practice divides hardness testing into two categories: macrohardness and microhardness. Macrohardness refers to testing with applied loads on the indenter of more than 1 kg and covers, for example, the testing of tools, dies, and sheet material in the heavier gages. In microhardness testing, applied loads are 1 kg and below, and material being tested is very thin (down to 0.0125 mm, or 0.0005 in.) [8] Therefore, we can say that each method has benefits and disadvantages. The presence of an independent device for each test is required in industrial institutions, and universal hardness equipment does not replace independent devices.

4. Effect of indentation method

The penetration tool is usually chosen according to the type of test, and here is important for tester to be a person has a sufficient experience in metallurgical engineering to distinguish the requirements for a specific type of hardness test, as the correct starting point lies in choosing the required testing method. Most of the raw materials are in the same condition. In most cases, the metallurgist or designer identifies the type of raw material by writing the symbol of alloy according to standard specifications ,this symbol will indicate the alloying elements content of the material .From this point, the tester must have sufficient knowledge in metallurgy to be able to make the correct decision of the selection of hardness test type, otherwise it will lead to defects of penetration tool due to plastic deformation which occurs for indenter so a change in the dimensions of the indenter will occurs then an error in the hardness measurement take place.

5. Effect of environment

It is naturally that there is an effect of the work environment on the result of any test. As we said, Brinell and Vickers tests require a magnifying glass with direct lighting. This means that the test laboratory room must be dark enough during the test and

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the sunlight does not penetrate the room because it will cause an error while using the Rockwell test, the lighting effect does not influence on result. Also the noise may cause error in results due to a loss of concentration of tester .Also the presence of vibrations arising from workshop machines such as turning and milling machines which close to the lab. Room may cause instability of the testing system and this cause measurement error.

6. Effect of calibration

In fact, there are two types of calibration methods. The first is called annual calibration and is carried out by a specialized team with accreditation in recognized international scientific institutions, so that the device is calibrated, specifically to calibrate the value of the applied load and match it to specifications and find deviations from the optimal reading, while there is temporary calibration of the device that depends on matching the reading. For the device using standard samples attached to the device on which the hardness values are recorded in order to find the deviation of the device and adjust it mathematically if it exists. Also it is required to perform measurements to indenters' dimensions using reflected light projectors to determine the presence or absence of plastic deformation of the penetration tool or any other defects.

IV. CONCLUSIONS

1. Application of equilibrium heat treatment to steel specimens give lower hardness values as compared to specimens which treated by non- equilibrium conditions.
2. Phase transformation is only occurs at condition of non-equilibrium heat treatments for high carbon steel specimens.
3. Low carbon steel specimens influenced by equilibrium heat treatments only.
4. High carbon steel specimens influenced by equilibrium and non-equilibrium heat treatments.
5. Rockwell hardness test is considered the quickest test to perform with least error compared to other methods of hardness tests.
6. Conversion table of hardness values give estimation only in comparison between hardness tests.
7. The environment conditions of hardness tests certainly influence on measurements.
8. Hardness tests that use magnification lenses require tester with full power of sight.

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