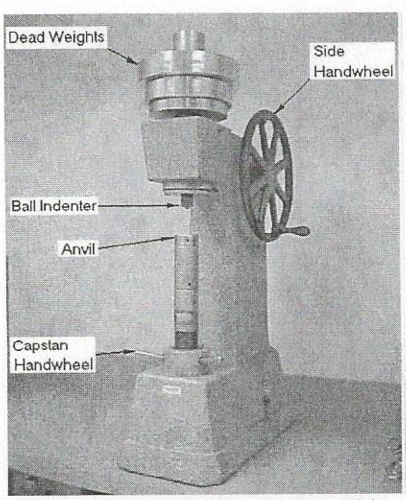
Hardness

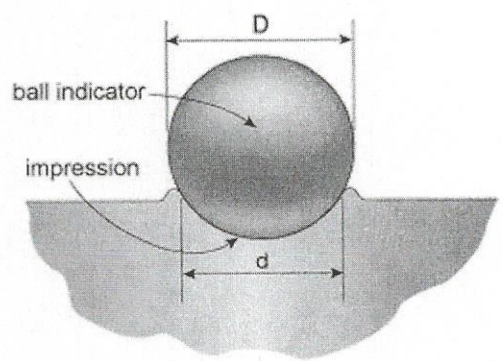
Hardness is one of the most basic mechanical properties of engineering materials.
Hardness test is practical and provide a quick assessment and the result can be used as a good indicator for material selections. This is for example, the selection of materials suitable for metal forming dies or cutting tools. Hardness test is also employed for quality assurance in parts which require high wear resistance such as gears.

The nomenclature of hardness comes in various terms depending on the techniques used for hardness testing and also depends on the hardness levels of various types of materials. A scratch hardness test is generally used for minerals, giving a wide range of hardness values in a Moh.s scale at minimum and maximum values of 1 and 10 respectively. For example, talcum provides the lowest value of 1 while diamond gives the highest of 10. The basic principle is that the harder material will leave a scratch on a softer material. Hardness values of metals generally fall in a range of 4-8 in Moh.s scale, which is not practical to differentiate hardness properties for engineering applications. Therefore, indentation hardness measurement is conveniently used for metallic materials. A deeper or wider indentation indicates a less resistance to plastic deformation of the material being tested, resulting in a lower hardness value.

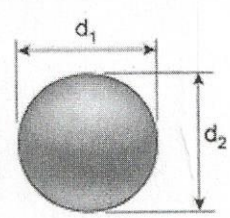
The indentation techniques involve Brinell, Rockwell, Vickers and Knoop. Different types of indenters are applied for each type. The standard test methods according to the American Society Testing and Materials (ASTM) available are, for instance, ASTM E10-07a (Standard test method for Brinell hardness of metallic materials), ASTM E18-08 (Standard test method for Rockwell hardness of metallic materials) and ASTM E92-41 (Standard test method for Vickers hardness of metallic materials) These hardness testing techniques are selected in relation to specimen dimensions, type of materials and the required hardness information. Their principles and testing methods are mentioned as follow.

1. ***Brinell Hardness Test***





(a) Brinell indentation



(b) measurement of impression diameter

Brinell hardness test was invented by J.A. Brinell in 1900 using a steel ball indenter with a 10 mm diameter. The steel ball is pressed on a metal surface to provide an impression as demonstrated in figure 1. This impression should not be distorted and must not be too deep since this might cause too much of plastic deformation, leading to errors of the hardness values.

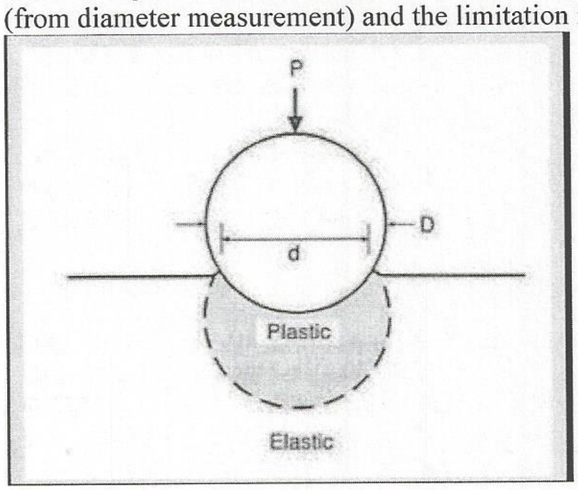
Different levels of material hardness result in impression of various diameters and depths. Therefore different loads are used for hardness testing of different materials as listed in table 1. Hard metals such as steels require a 3,000 kgf load while brass and aluminum involve the loads of 2,000 and 1,000 or 500 kgf respectively. For materials with very high hardness, a tungsten carbide ball is utilized to avoid the distortion of the ball.
In practice, pressing of the steel ball on to the metal surface is carried out for 30 second, followed by measuring two values of impression diameters normal to each other using a low magnification macroscope. An average value is used for the calculation according to equation 1

$$\mathbf{BHN = P/\{(\pi D/2).(D-\sqrt{D^2 - d^2})\} = P/(\pi D t)}$$

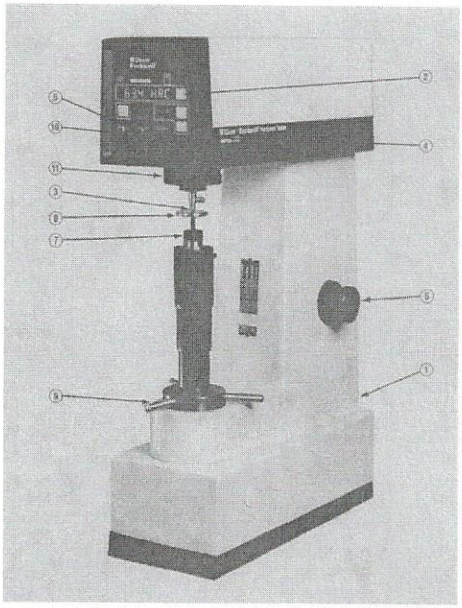
Where:

P is the applied load, kg
D is the diameter of the steel ball, mm
d is the diameter of the indentation, mm
t is the depth of impression, mm

Note: This BHN values has a unit of kgf.mm-2 (1 kgf.mm-2 = 9.8 MPa) which cannot be compared to the average mean pressure on the impression. Generally, the metal surface should be flat without oxide scales or debris because these will significantly affect the hardness values obtained. A good sampling size due to a large steel ball diameter is advantageous for materials with highly different microstructures or microstructural heterogeneity. Scratches or surface roughness have very small effects on the hardness values measured. However, there are some disadvantages of Brinell hardness test. These are errors arising from the operator themselves (from diameter measurement) and the limitation in measuring of too small samples.



If we considered the plastic zone beneath the Brinell indenter, this plastic region is surrounded by elastic material which obstructs the plastic flow. This condition is said to be plane strain compressive where plastic deformation is limited. If the metal is very rigid, the metal flow upwards surrounding the indenter is possible as illustrated in figure



1. Power switch
2. Test scale scroll key
3. Indenter
4. Indenter display
5. Major load (kg) display
6. Weight selector dial
7. Anvil
8. Specimen
9. Capstan handwheel
10. Minor load (kg) display

Figure 2 – A Wilson Rockwell Model

However this situation is rarely seen because the metal displaced by the indenter is accounted for by the reduced volume of elastic material.

Rockwell Hardness Test

Rockwell hardness test is commonly used among industrial practices because the Rockwell testing machine offers a quick and practical operation and can also minimize errors arising from the operator. The depth of an indentation determines the hardness values. There are two types of indenters, Brale and steel ball indenters. The former is a round-tip cone with an included angle of 120o whereas the latter is a hardened steel ball with their sizes ranging from 1.6-12.7 mm. Therefore different combinations of indenters and loads selected are suitable for hardness testing of various materials. This is for example; the R scale is employed for soft materials such as polymers while the A scale is suitable for hardness testing of hard materials such as tool materials according to table 1.

The testing procedure starts with indenting a flatly ground metal surface with a diamond or hardened steel ball with a minor load of 10 kgf to position the metal surface as shown in figure above.

The depth of the impression caused by the minor load will be recorded as $H1$onto the machine before applying a major load level according to a standard as shown in table 2 and is recorded as $H2$. The difference of the depths ($\Delta H= H1-H2$) when applying the minor and the major loads indicates the hardness value of the material. If the depth difference is small, the deformation resistance of the metal is high, resulting in a high Rockwell hardness value. The hardness value will be displayed on a dial or a screen, having 100 divisions and each division represents a depth of 0.002 mm. Therefore the hardness value can be determined from a relationship as follows

$$HRX = M-\Delta H/2$$

Where ΔH is $H1-H2$ and M is the maximum scale which equals 100 in general for testing with the diamond indenter (scale A, C and D). The M value equals 130 when testing with a steel ball for Rockwell scales B, E, M, and R.

The Rockwell hardness units are in RA, RB and RC (or HRA, HRB, HRC), depending on material's hardness. Tables 1 and 2 summarize loads and types of an indenter utilized for each scale. There are two types of indenters used, Brale indenter and steel ball indenters as mentioned previously. The applied major loads vary from 60, 100 and 150 kgf, also depending on the Rockwell hardness scale utilized. For instance, hardened steel is tested on a Rockwell scale C using a Brale indenter and at a major load of 150 kgf. On the Rockwell scale C, the obtained hardness values range from RC 20 F RC 70. Metals with lower hardness are tested on a Rockwell scale B using a 1.6 mm diameter steel ball at a 100 kgf major load, providing RB 0 F RB 100 hardness values. Rockwell scale A offers a wider range of hardness values which can be used to test materials ranging from annealed brass to cemented carbide. Due to high accuracy, the Rockwell hardness test is commonly conducted for measuring hardness of heat-treated steels. Furthermore, the smaller indenter (in comparison to that of Brinell hardness test) facilitates hardness measurement in small areas. However, this technique requires good surface preparation since the hardness values obtained is significantly affected by rough and scratched surfaces. There are several considerations for Rockwell hardness test:

- Require clean and well positioned indenter and anvil
- The test sample should be clean, dry, smooth and oxide-free surface
- The surface should be flat and perpendicular to the indenter
- Low reading of hardness value might be expected in cylindrical surfaces
- Specimen thickness should be 10 times higher than the depth of the indenter
- The spacing between the indentations should be 3 to 5 times of the indentation diameter

Loading speed should be standardized.

Vickers Hardness Test

Vickers hardness test requires a diamond pyramid indenter with an included angle of 136°. This technique is also called a diamond pyramid hardness test (DPH) according to the shape of the indenter. To carry on the test, the diamond indenter is pressed on to a prepared metal surface to cause a square-based pyramid indentation as illustrated in figure 4.

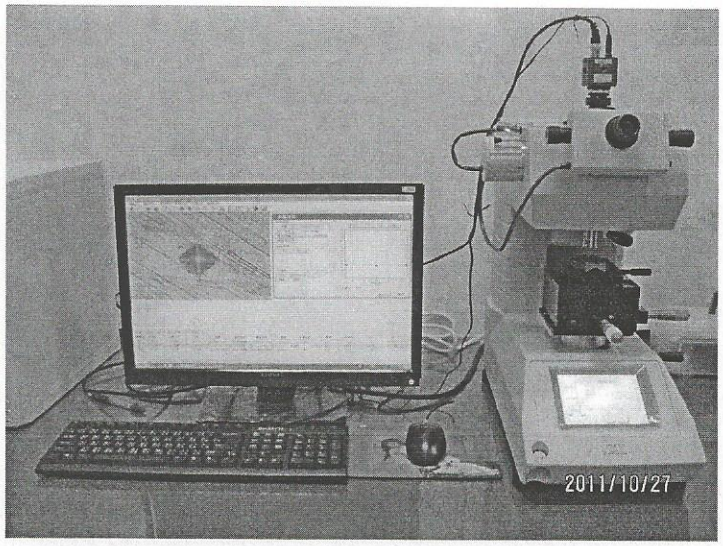
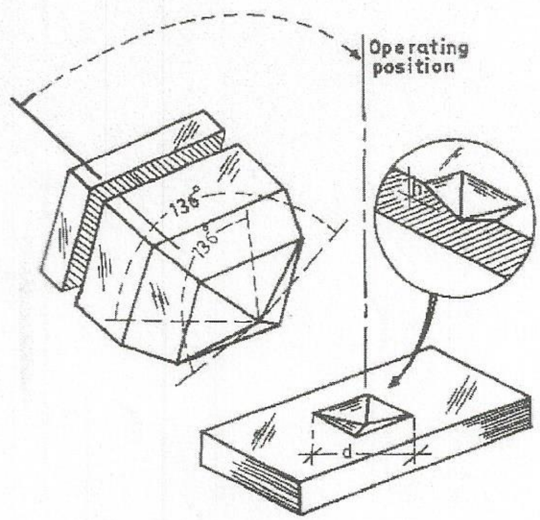


Figure: Vicker Micro hardness Equipment and Data acquisition.



The Vickers hardness value (VHN) can be calculated from the applied load divided by areas of indentation, at which the latter is derived from the diagonals of the pyramid as expressed in the equation below

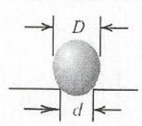
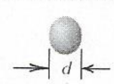
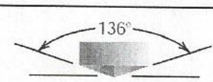
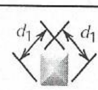
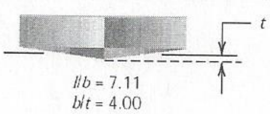
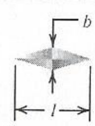
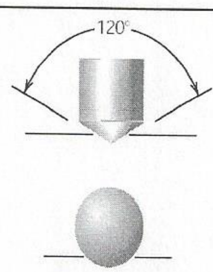
$$VHN = 2PSin(\theta/2)\ /d^2 = 1854.4P/d^2$$

Where P is the applied load in grams (*g*), □□is the indenter face angle of 136□, and d is the mean diagonal length in □*m*. The constant 1854.4 incorporates the value of *sin*(□/2) and other conversion factors to give VHN a unit of kg/mm^2.

Procedure for microhardness test:

1. Turn on the tester.
2. Select and install the indenter (Vickers or Knoop), if not already installed.
3. Place the weights selected on the loading pan.
4. Place the specimen in the tester and turn the 40□□objective lens into place. Focus on the specimen surface with the focusing control until surface features can be seen.
5. Gently turn the loading handle clockwise to raise the weights and the indenter, and turn the indenter into place. Slowly release the loading handle counter-clockwise to apply the load. Leave the indenter on the specimen for 10 to 15 s.
6. Raise the indenter by turning the loading handle clockwise gently, and turn the objective lens back into place.
7. Focus on the specimen surface to view the indentation. Measure length of the long diagonal (Knoop) or both diagonals (Vickers) of the indentation with the scale in the microscope. The numbers on the scale are length measured in 0.001 mm. alternatively, the diagonal lengths can be determined by moving a point on the scale from a corner to the opposite corner of the impression under microscope and noting the difference in micrometer readings (numbers on the fine scale are in 0.01 mm).
8. Calculate microhardness number using the appropriate formula.

Various Hardness Techniques.

Test	*Indenter*	*Shape of Indentation*		*Load*	*Formula for Hardness Number*[a]
		Side View	*Top View*		
Brinell	10-mm sphere of steel or tungsten carbide			*P*	$HB = \frac{2P}{\pi D[D - \sqrt{D^2 - d^2}]}$
Vickers microhardness	Diamond pyramid			*P*	$HV = 1.854P/d_1^2$
Knoop microhardness	Diamond pyramid			*P*	$HK = 14.2P/l^2$
Rockwell and Superficial Rockwell	Diamond cone; $\frac{1}{16}, \frac{1}{8}, \frac{1}{4}, \frac{1}{2}$ in. diameter steel spheres			60 kg, 100 kg, 150 kg (Rockwell); 15 kg, 30 kg, 45 kg (Superficial Rockwell)	