Hardness Tests

The term hardness may be defined as a material’s resistance to localized plastic deformation (e.g., a small dent or a scratch). The hardness of materials is often equated with wear resistance and durability. Thus, early attempts to quantify hardness led to the adoption of Moh’s scale which was used originally to assess the relative hardness of minerals. The Moh’s hardness of a mineral is determined by observing whether its surface is scratched by a substance of known or defined hardness. Moh’s scale of hardness consists of a list of materials arranged in order of hardness, with diamond the hardest of all, with a hardness index 10, at the head of the hardness scale and talc, with an index of 1, at the foot of hardness scale, Table 1. For example, if some material is scratched by apatite but not by fluorite, its hardness on the Mohs scale would fall between 4 and 5.

Table 1: ***Moh’s scale of hardness***

Talc	1		Feldspar	6	
Gypsum	2		Quartz	7	
Calcite	3		Topaz	8	
Fluorite	4		Corundum	9	
Apatite	5		Diamond	10	

Obviously, there was considerable room for error in judging what was a ‘normal’ scratch. For this reason, modern methods of hardness testing really measure the material’ s resistance to penetration rather than to abrasion. Quantitative hardness techniques have been developed over the years.

There are many types of hardness tests. The most important are penetration, indentation, tests. in which a small indenter is forced into the surface of a material to be tested, under controlled conditions of load and rate of application. The depth or size of the resulting indentation is measured, which in turn is related to a hardness number; the softer the material, the larger and deeper the indentation, and the lower the hardness index number.

The Brinell hardness test

In Brinell tests a hard, spherical hardened steel (or tungsten carbide) indenter is forced into the surface of the material to be tested by means of a suitable standard load, Figure 1. The load is maintained constant for a specified time (between 10 and 30 s). Harder materials require greater applied loads. The Brinell hardness number, HB, is a function of both the magnitude of the load and the diameter of the resulting indentation. The diameter of the impression is then measured, using some form of calibrated microscope.

Semiautomatic techniques for measuring Brinell hardness are available. These employ optical scanning systems consisting of a digital camera mounted on a flexible probe, which allows positioning of the camera over the indentation. Data from the camera are transferred to a computer that analyzes the indentation, determines its size, and then calculates the Brinell hardness number. For this technique, surface finish requirements are normally more stringent than for manual measurements. The Brinell hardness number (HB) is found from:

$$H = \frac{Load\ P}{area\ of\ curved\ surface\ of\ the\ impression\ A}$$

If D is the diameter of the ball and d that of the impression, it can be shown that:

$$A = \frac{\pi}{2} D\left(D - \sqrt{D^2 - d^2}\right)$$

It follows that:

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

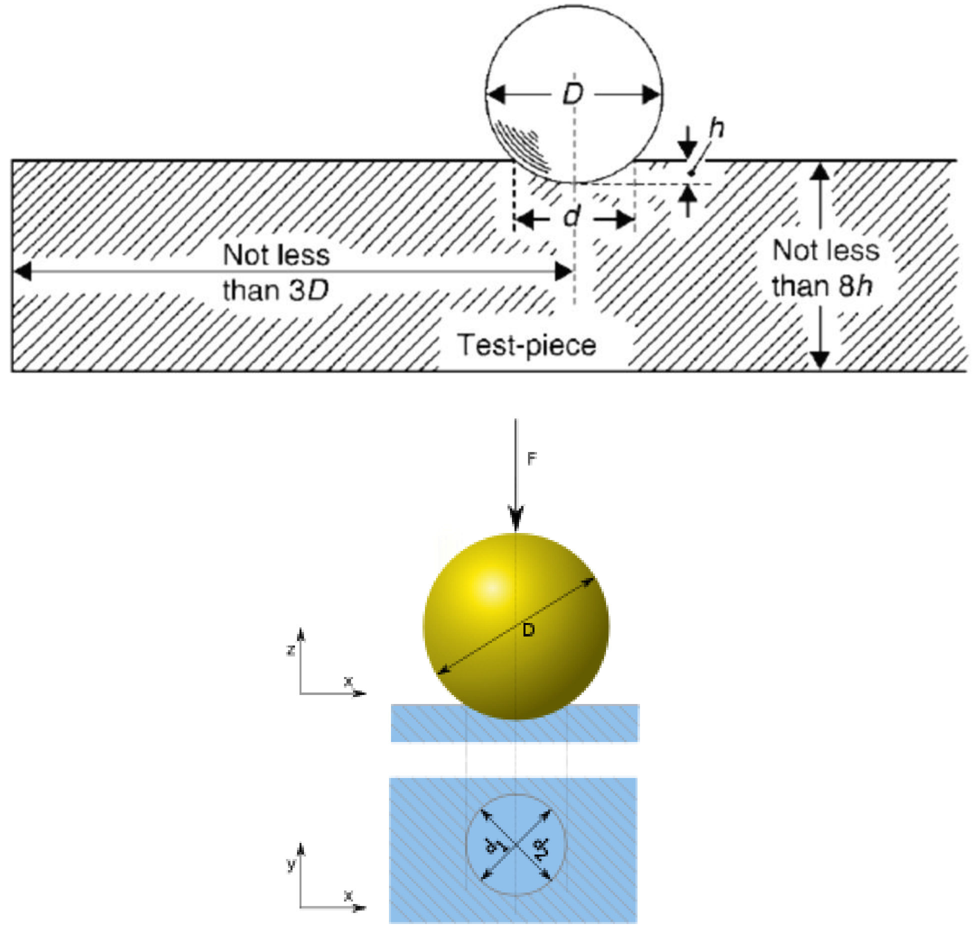


Figure 1: Brinell hardness test

In carrying out a Brinell test, certain conditions must be fulfilled. First, *the depth of impression* must not be too great relative to the thickness of the test-piece, otherwise we may produce the situation shown in Figure 2A. Hence, it is recommended that the thickness of the test-piece shall be at least 8 times the depth of the impression. *The width of the test-piece* must also be adequate to support the load. otherwise the edges of the impression may collapse due to the lack of support and so give a falsely low reading.

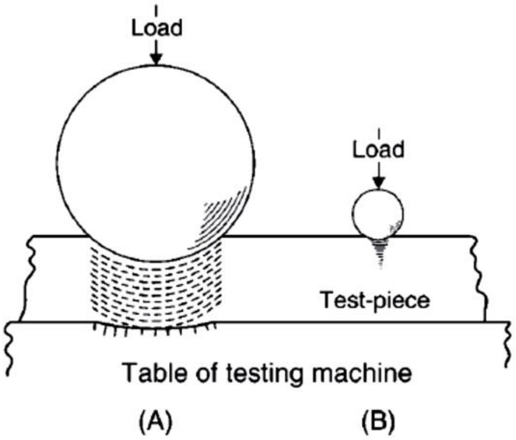


Figure 2: This illustrates the necessity of using the correct ball diameter in relation to the thickness of the test-piece.

Balls of 10, 5 and 1 mm diameter are available; so, one appropriate to the thickness of the test-piece should be chosen, bearing in mind that the larger the ball it is possible to use, the more accurate is the result likely to be.

Having decided upon a suitable ball, we must now select a *load* which will produce an impression of reasonable proportions. If, for example, in testing a soft metal we use a load which is too great relative to the size of the ball, we shall get an impression similar to that indicated in Figure 3 A . Here, the ball has sunk to its full diameter, and the result is meaningless. On the other hand, the impression shown in Figure 3B would be obtained if the load were too small relative to the ball diameter, and here the result would be uncertain. For different materials, then, the ratio P / D ^{2} has been standardized Table 2 in order to obtain accurate and comparable results.

P is still measured in ‘ kg force ’ and D in mm.

As an example, in testing a piece of steel, we can use a 10 mm ball in conjunction with a 3000 kgf load, a 5 mm ball with a 750 kgf load or a 1 mm ball with a 30 kgf load. As mentioned earlier, the choice of ball diameter D will rest with the thickness of the test-piece, whilst the load to be used with it will be determined from the appropriate P / D ^{2} ratio.

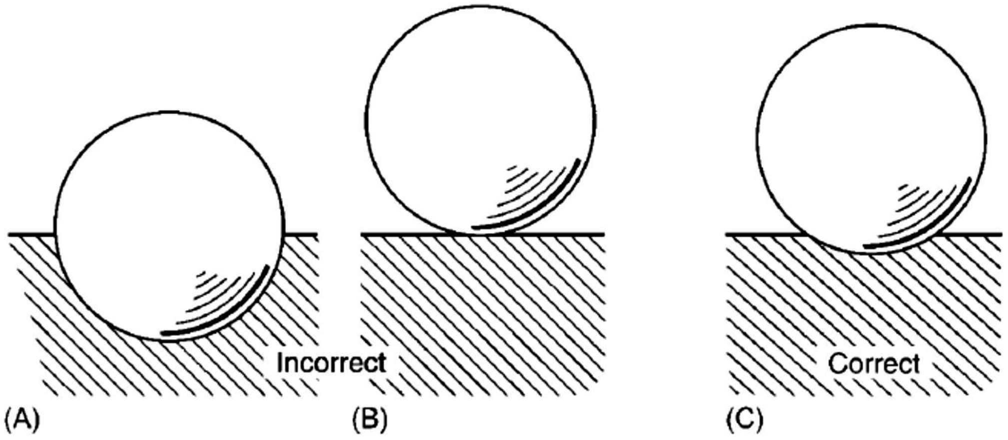
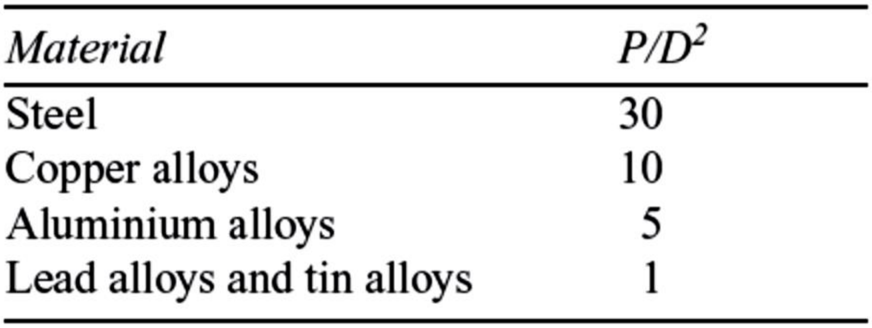


Figure 3: ***It is essential to use the correct P/D ^{2} ratio for the material being tested.***

Table 2: P/D ^{2} ratios for the Brinell test



Material	*P/D²*
Steel	30
Copper alloys	10
Aluminium alloys	5
Lead alloys and tin alloys	1

The Rockwell hardness test

In the Rockwell test, a spherical indenter is used for softer materials (Rockwell B scale), and a conical indenter is used for hard materials (Rockwell C scale) is used. The test-piece, which needs no preparation save the removal of dirt and scale from the surface, is placed on the table of the instrument and the indenter is brought into contact with the surface under 'light load ' . The indenter is first loaded with a minor load of 10 kg f, while the indicator for measuring the depth of the impression is set to zero. The appropriate major load is then applied, and, after its removal, the dial gauge records the depth of the impression in terms of Rockwell numbers, Figure 4.

Rockwell testing has two important advantages as compared to other tests previously discussed:

- Application and retention of the minor load during the test prepares the surface upon which the incremental penetration depth due to the major load is measured.
- The hardness value is read directly on the dial gage without the necessity for measuring the indentation dimensions, as in other hardness testing methods.

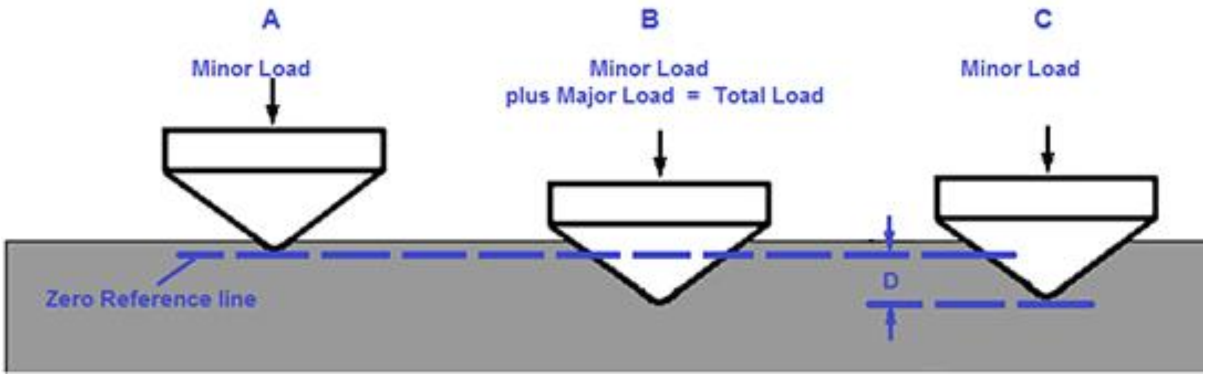


Figure 4: The Rockwell hardness test

The Vickers hardness test

The indenter of the Vickers test is a pyramid with a square base. The side angles are precisely defined by the standards (136°). The operating diagram of this test is given in Figure 5. A square indent is thus produced, and the user measures the average diagonal length and again reads the hardness number (*H*V) from the tables

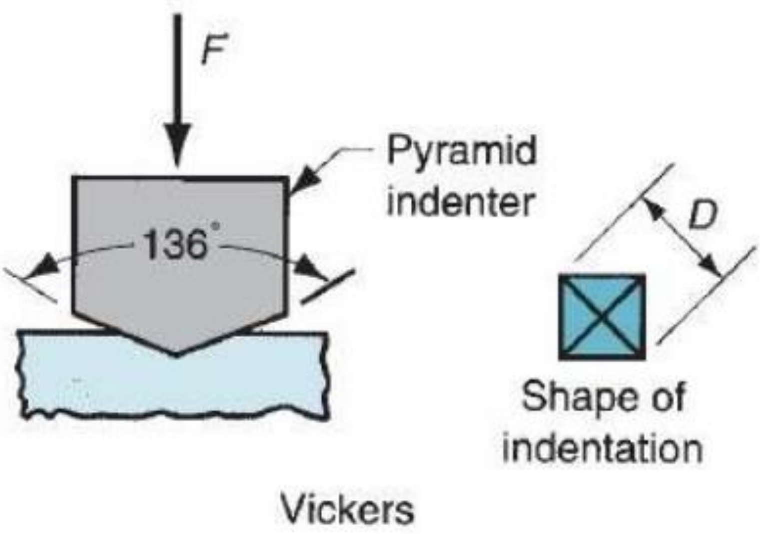


Figure 5: The Vickers hardness test

One great advantage of this is that all the impressions will be the same square shape, regardless of how big an indentation force is used. Consequently, the operator does not have to choose a P/D ^{2} ratio as he does in the Brinell test, though he must still observe the relationship between the depth of impression and thickness of specimen, for reasons similar to those indicated in the case of the Brinell test and illustrated in Figure 2 . Here, the thickness needs to be at least 1.5 times the diagonal length of the Indentation.

A further advantage of the Vickers hardness test is that the hardness values for very hard materials (above an index of 500) are likely to be more accurate than the corresponding Brinell numbers – a diamond does not deform under high pressure to the same extent as does a steel ball, and so the result will be less uncertain.

For steels there is a useful empirical relationship between the UTS (in MPa) and HV (in kgf mm^{-2}), namely:

UTS ≈ 3.2 HV

The size of the impression is related to hardness in the same way as is the Brinell number

$$H = \frac{Load\ P}{surface\ area\ of\ indentation A}$$

Since the impression made by the diamond is generally much smaller than that produced by the Brinell indenter, a smoother surface finish is required on the test-piece. The Vickers test form such small indentations that a microscope is required to obtain the measurement, Figure 6.

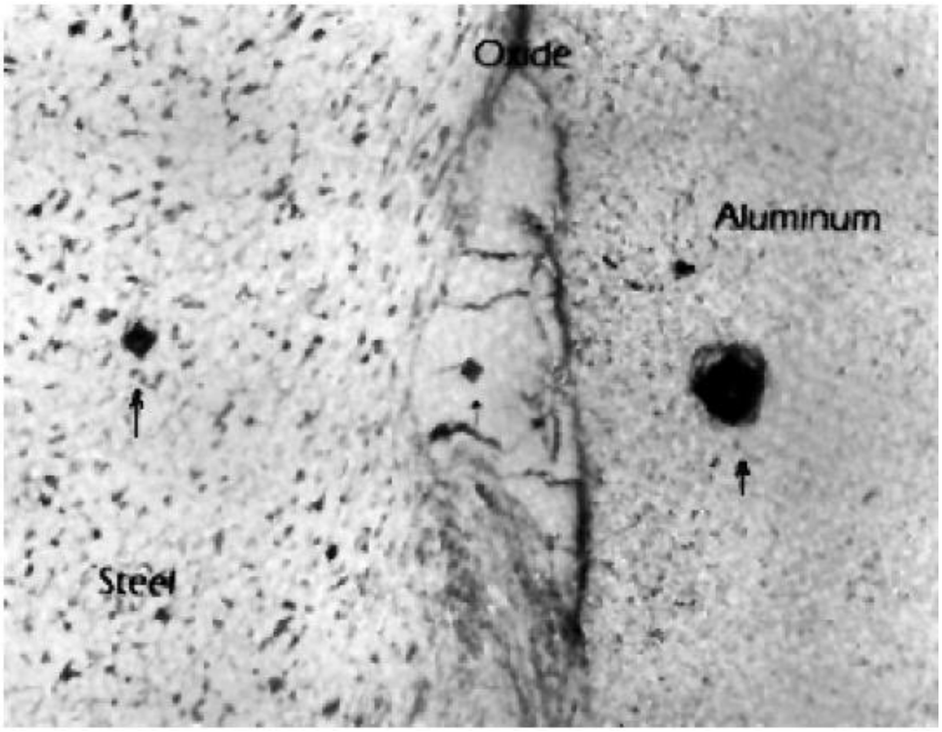


Figure 6: Microhardness impressions in an explosive bond joining aluminum to steel.

The Knoop test

The Knoop test uses a diamond pyramidal indenter of apex angles 130° and 172.5°, thus giving a rhombohedral impression with one diagonal (L) being 7 × longer than the other and with a depth which is one thirtieth of L. It is particularly useful for measuring the relative harnesses of brittle materials, such as glasses and ceramics, when lower loads (P) are employed than in the Vickers test.

The Knoop Hardness Number (KHN, in kgf mm^{-2}) is given by the relation:

$KHN = 14.229\ P/L^2$.

Figure 7 shows a comparison between Vickers and Knoop indenters and indentations. A summery of some of hardness testing techniques is illustrated in Table 3

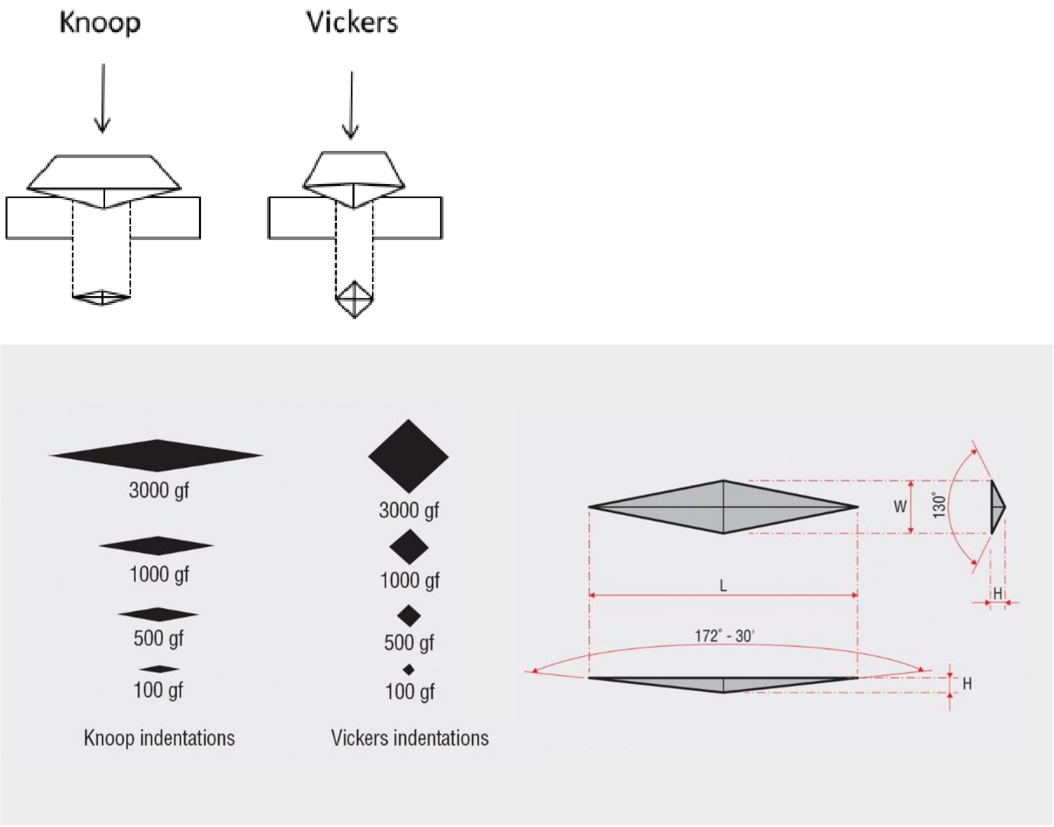
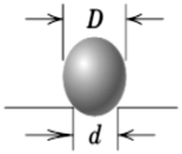
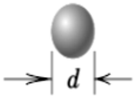
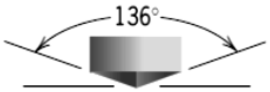
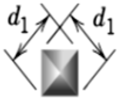
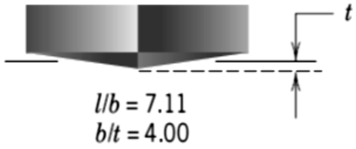
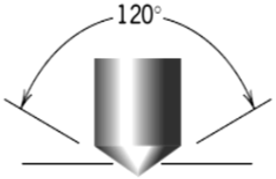
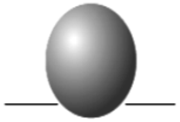
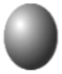
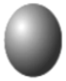


Figure 7: Vickers and Knoop indenters and indentations

Table 3: Hardness testing 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	$\mathrm{HB} = \dfrac{2P}{\pi D[D - \sqrt{D^2 - d^2}]}$
Vickers microhardness	Diamond pyramid			P	$\mathrm{HV} = 1.854P/d_1^2$
Knoop microhardness	Diamond pyramid			P	$\mathrm{HK} = 14.2P/l^2$
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	

Nano-hardness (Nano indentation hardness testing)

Nano indenting is a new method to characterize material mechanical properties on a very small scale. Features less than 100 nm across, as well as thin films less than 5 nm thick, can be evaluated. The principle remains the same, but the observation device is much finer. The indentation curve is recorded and the profilometry of surfaces is achieved, for example, with an atomic force microscope. The area for testing is located by AFM imaging, and indentations and scratching marks are imaged by AFM after testing. A three-sided, pyramid-shaped diamond probe tip is typically used to indent, scratch the sample, as can be seen in Figure 8. For indentation, the probe is forced into the surface at a selected rate and to a selected maximum force. In scratching, the probe is dragged across the sample surface. The force, rate, length and angle of the scratch is controlled.

This method enables us to determine the hardness of the grains one by one in a two-phase material or, for example, the effectiveness of treatments on very low depths like ion implantation.

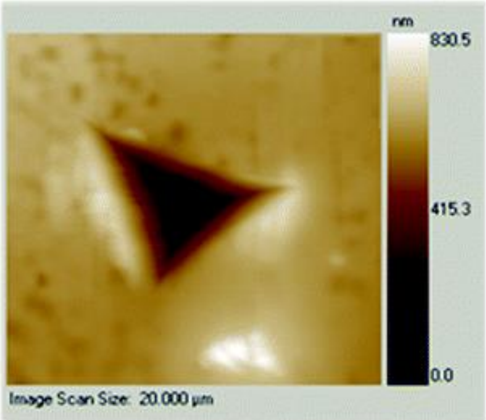


Figure 8: ***Nano indentation testing***