Experiment of Part 2
Hardness Testing and Hardenability

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Course No: IE 0906421

1. Objectives.

To help the students to become more familiar with all aspects of material's hardness, including; what is hardness, hardness measurement methods, common concepts of hardness, and hardness vs. hardenability.

2. What is Hardness?

Hardness can be defined as "*as the ability of a material to resist permanent indentation or deformation when in contact with an indenter under load"* [3]. The greater the hardness of the metal, the greater resistance it has to deformation. In metallurgy hardness is defined as the ability of a material to resist plastic deformation. Hardness also can be described as the resistance of a substance to being scratched by another substance. Since hardness is defined as the resistance of a material to indentation, a hardness test can be performed when pressing a pointed or rounded indenter into a surface under a static load.

Harry chandler claimed [1] that hardness has a variety of meanings "To the metals industry, it may be thought of as resistance to permanent deformation. To the metallurgist, it means resistance to penetration. To the lubrication engineer, it means resistance to wear. To the design engineer, it is a measure of flow stress. To the mineralogist, it means resistance to scratching, and to the machinist, it means resistance to machining. Hardness may also be referred to as mean contact pressure. All of these characteristics are related to the plastic flow stress of materials".

3. Measuring Hardness

Generally a hardness test consists of pressing an indenter of known geometry and mechanical properties into the test material. The hardness of the material is quantified using one of a variety of scales that directly or indirectly indicate the contact pressure involved in deforming the test surface. Since the indenter is pressed into the material during testing, hardness is also viewed as the ability of a material to resist compressive loads. The indenter may be spherical (Brinell test), pyramidal (Vickers and Knoop tests), or conical (Rockwell test). In the Brinell, Vickers, and Knoop tests, hardness value is the load supported by unit area of the indentation, expressed in kilograms per square millimeter (kgf/mm^2). In the Rockwell tests, the depth of indentation at a prescribed load is determined and converted to a hardness number (without measurement units), which is inversely related to the depth. The most common hardness test methods that used in today`s industries are;

1. Rockwell hardness test
2. Brinell hardness test
3. Vickers hardness test
4. Knoop hardness test
5. Shore hardness test

Depending on the applied forces, measurement of hardness can be classified into macro-, micro- or nano- scale hardness measurement. Macro-hardness testing method investigates the mechanical property data for the bulk material from a small sample. It is also used for the quality control of surface treatments processes. However, the macro-indentation depth is important when concerned with coatings and surface properties of importance to friction and wear processes. Vickers or Knoop hardness that determined by forcing a tip into the surface of a sample material under 15 to 1000 gf load is Microhardness hardness test. The indentations are measured with a microscope [2]. Nano-hardness tests measure hardness based on a very small indentation, on the order of 1 nano-Newton, where a precise hardness measurement are obtained with special purpose tools and equipment.

Hardness tests are no longer limited to metals, and the currently available tools and procedures cover a vast range of materials including polymers, elastomers, thin films, semiconductors, and ceramics.

4. Rockwell Hardness Test

The Rockwell hardness test is defined in ASTM E 18 and several other standards (Table 1).There are two types of Rockwell tests: Rockwell and superficial Rockwell. In Rockwell testing, the minor load is 10 kgf, and the major load is 60, 100, or 150 kgf. In superficial Rockwell testing, the minor load is 3 kgf, and major loads are 15, 30, or 45 kgf. In both tests, the indenter may be either a diamond cone or a hardened ball depending principally on the characteristics of the material being tested.

Table 1 Selected Rockwell hardness test standards for metals and hardmetals

Standard No.	Title
ASTM B 294	Standard Test Method for Hardness Testing of Cemented Carbides
ASTM E 18	Test Methods for Hardness and Rockwell Superficial Hardness of Metallic Materials
ASTM E 1842	Test Method for Macro-Rockwell Hardness Testing of Metallic Materials
BS 5600-4.5	Powder Metallurgical Materials and Products—Methods of Testing and Chemical Analysis of Hardmetals—Rockwell Hardness Test (Scale A)
BS EN ISO 6508-1	Metallic Materials—Rockwell Hardness Test—Part 1: Test Method (Scales A, B, C, D, E, F, G, H, K, N, T)
BS EN ISO 6508-2	Metallic Materials—Rockwell Hardness Test—Part 2: Verification and Calibration of Testing Machines (Scales A, B, C, D, E, F, G, H, K, N, T)
BS EN ISO 6508-3	Metallic Materials—Rockwell Hardness Test—Part 3: Calibration of Reference Blocks (Scales A, B, C, D, E, F, G, H, K, N, T)
ISO 3738-1	Hardmetals—Rockwell Hardness Test (Scale A)—Part 1: Test Method
ISO 3738-2	Hardmetals—Rockwell Hardness Test (Scale A)—Part 2: Preparation and Calibration of Standard Test Blocks
JIS B 7726	Rockwell Hardness Test—Verification of Testing Machines
JIS B 7730	Rockwell Hardness Test—Calibration of Reference Blocks

Hardened ball indenters with diameters of 1.588, 3.175, 6.35, and 12.7 mm are used. Figure 1(A) shows a Rockwell test consists of checking the resistance of a sample, to be penetrated by a hard metal ball or by a conical shaped diamond, under the pressure of a load. This test proceeds in two steps. At first the penetration start point (zero) under a minor or preliminary load is determined, and the second step happens under a major load. The latent deformation measured after releasing the major load, is a direct measure of the Rockwell hardness, which is given on the scale of the dial gauge.

Rockwell hardness values are expressed as a combination of hardness number and a scale symbol representing the indenter and the minor and major loads. The Rockwell hardness is expressed by the symbol HR and the scale designation. For example, 64.0 HRC represents the Rockwell hardness number of 64.0 on the Rockwell C scale; 81.3 HR30N represents the Rockwell superficial hardness number of 81.3 on the Rockwell 30N scale. Because of the changeover to carbide balls, the designation for the ball scales will require the use of an S or W to indicate the ball used. For example, a HRB scale reading of 80.0 obtained using a steel ball would be labeled 80.0 HRBS, while the same result using a carbide ball would be designated 80.0 HRBW. There are 30 different scales, defined by the combination of the indenter and the minor and major loads (Tables 2).

Table 2 Rockwell standard hardness

Scale symbol	Indenter	Major load, kgf	Typical applications
A	Diamond (two scales—carbide and steel)	60	Cemented carbides, thin steel, and shallow case-hardened steel
B	$\frac{1}{16}$ in. (1.588 mm) ball	100	Copper alloys, soft steels, aluminum alloys, malleable iron
C	Diamond	150	Steel, hard cast irons, pearlitic malleable iron, titanium, deep case-hardened steel, and other materials harder than 100 HRB
D	Diamond	100	Thin steel and medium case-hardened steel and pearlitic malleable iron
E	⅛ in. (3.175 mm) ball	100	Cast iron, aluminum and magnesium alloys, bearing metals
F	$\frac{1}{16}$ in. (1.588 mm) ball	60	Annealed copper alloys, thin soft sheet metals
G	$\frac{1}{16}$ in. (1.588 mm) ball	150	Phosphor bronze, beryllium copper, malleable irons. Upper limit 92 HRG to avoid possible flattening of ball
H	⅛ in. (3.175 mm) ball	60	Aluminum, zinc, lead
K	⅛ in. (3.175 mm) ball	150	Bearing metals and other very soft or thin materials. Use smallest ball and heaviest load that do not produce anvil effect.
L	¼ in. (6.350 mm) ball	60	Bearing metals and other very soft or thin materials. Use smallest ball and heaviest load that do not produce anvil effect.
M	¼ in. (6.350 mm) ball	100	Bearing metals and other very soft or thin materials. Use smallest ball and heaviest load that do not produce anvil effect.
P	¼ in. (6.350 mm) ball	150	Bearing metals and other very soft or thin materials. Use smallest ball and heaviest load that do not produce anvil effect.
R	½ in. (12.70 mm) ball	60	Bearing metals and other very soft or thin materials. Use smallest ball and heaviest load that do not produce anvil effect.
S	½ in. (12.70 mm) ball	100	Bearing metals and other very soft or thin materials. Use smallest ball and heaviest load that do not produce anvil effect.
V	½ in. (12.70 mm) ball	150	Bearing metals and other very soft or thin materials. Use smallest ball and heaviest load that do not produce anvil effect.

Source: ASTM E 18

To achieve still greater production rates, high-speed testers (Figure 1) are used. High-speed testers can be automated to include automatic feeding, testing, and tolerance sorting. Upper and lower tolerance limits can be set from an operator control panel. These testers allow test loads to be applied at high speed with short dwell times. Up to 1000 parts per hour can be tested. These testers are normally dedicated to specific hardness ranges

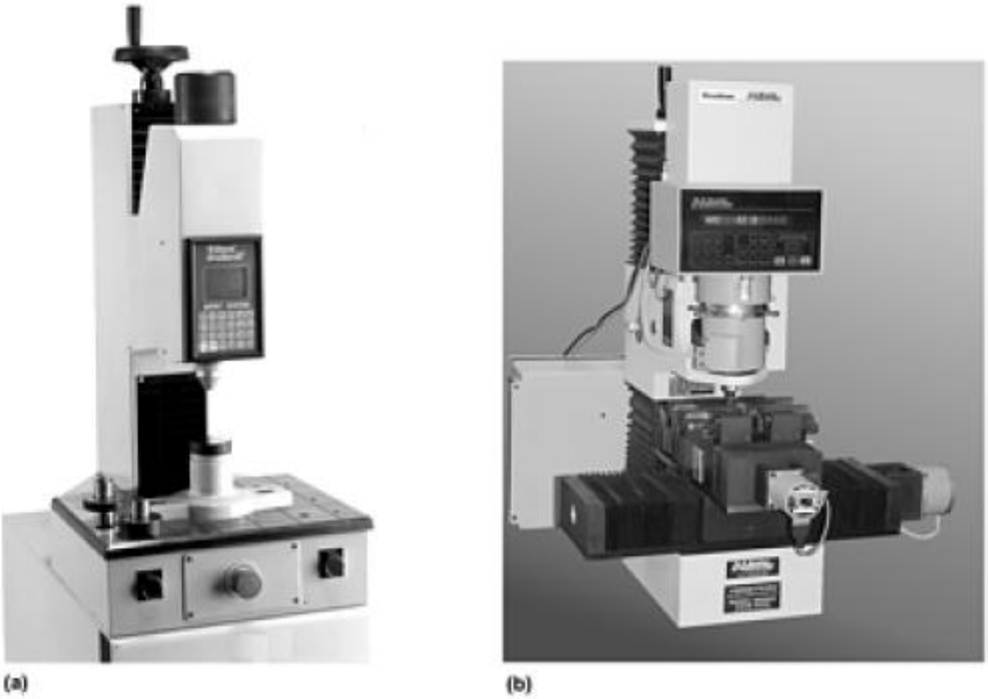


Figure 1. Production Rockwell testers. (a) High-speed Rockwell tester. (b) Automated Rockwell tester for high-rate testing, such as the setup shown for Jominy end-quench hardenability testing

5. Brinell Hardness Test

Brinell hardness test is conducted by forcing a steel or carbide sphere of a specified diameter under a specified load into the surface of a workpart and measuring the diameter of the indentation left. The Brinell number (BH) is computed by equation (1), it is obtained by dividing the load used, in kilograms, by the actual surface area of the indentation, in square millimeters. ASTM E-10 is a standard test for Brinell hardness of metallic materials. The load applied is usually 3,000, 1,500, or 500 kgf, the load is applied steadily for 10 to 15 seconds, and usually the diameter of the indentation is in the range 2.5 to 6.0 mm.

$$BH = \frac{2p}{\pi D\left(D - \sqrt{D^2 - d_i^2}\right)} \quad \text{..... (1)}$$

Where

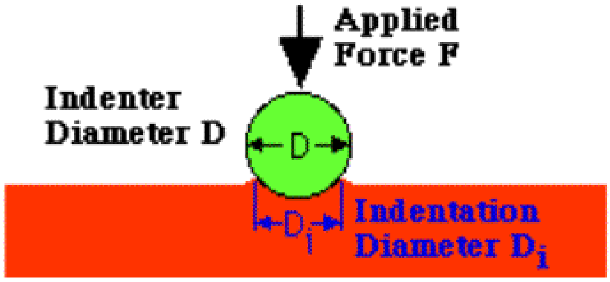
BH = *the Brinell hardness number*

p = *the imposed load in kg f*

D = *the diameter of the spherical indenter in mm*

$d\,i$ = *diameter of the resulting indenter impression in mm*

The maximum range of Brinell hardness values is 16 HB for very soft aluminum to 627 HB for hardened steels (approximately 60 HRC). Figure 2 (A) shows Brinell Hardness Tester, Figure 2 (B) depicts a simple presentation of Brinell hardness test.



(A) (B)

Figure 2. Brinell hardness Test

6. Vickers Hardness Test.

Vickers hardness is a measure of the hardness of a material, calculated from the size of an impression produced under load by a pyramid-shaped diamond indenter.

The indenter in Vickers test is a square-based pyramid whose opposite sides meet at the apex at an angle of 136º. The diamond is pressed into the surface of the workpart at loads ranging up to approximately 120 kilograms-force, and the size of the impression is measured by a microscope. The Vickers number (HV) is calculated using equation (2) and figure 3 (A).

$$HV = 1.854\left(\frac{p}{d^2}\right)$$

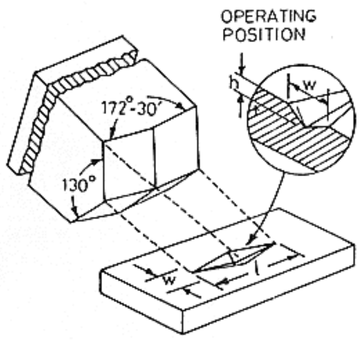
Where

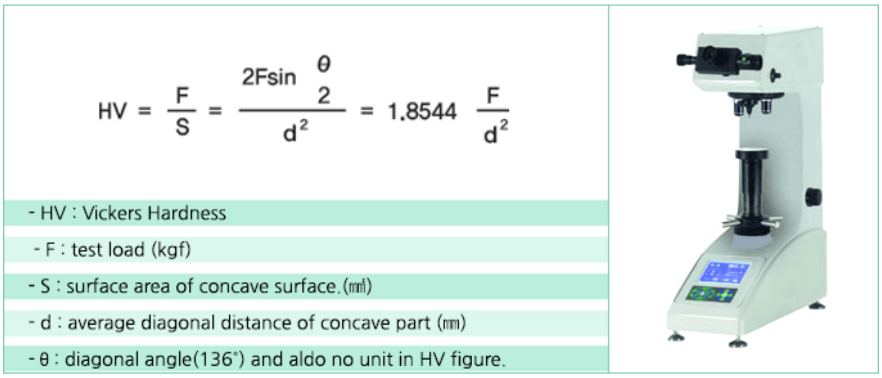
HV = *The Vickers number* ….. (2)

p = *the applied load in kilograms- force*

d^2 = *the area of the indentation measured in square millimetres*

The Vickers machine (as shown in figure 3 (B) is a floor standing unit that is rather more expensive than the Brinell or Rockwell machines





(A) (B)

Figure 3. Vickers Hardness Test

In summary, advantages of the Vickers test are:

1. Vickers hardness, in general, is independent of force when determined on homogeneous material, except possibly at forces below 5 kgf.
2. The edge or ends of the diagonals are usually well defined for measurement.
3. The indentations are geometrically similar, irrespective of size.
4. One continuous scale is used for a given force, from lowest to highest values.
5. Indenter deformation is negligible on hard material.

Disadvantages of the Vickers test are:

1. Test is slow and not well adapted for routine testing. Typical test and measurement times are in the one minute range.
2. Careful surface preparation of the specimen is necessary, especially for shallow indentations.
3. Measurement of diagonals is operator dependent, with possible eyestrain and fatigue adding to test errors.

7. Knoop hardness

In 1939, Frederick Knoop and his associates at the former National Bureau of Standards developed an alternate indenter based on a rhombohedral-shaped diamond with the long diagonal approximately seven times as long as the short diagonal (Fig. 4a). Figure 4(b) shows examples of Knoop indents to illustrate the influence of applied load on indent size. The Knoop indenter is used in the same machine as the Vickers indenter, and the test is conducted in exactly the same manner, except that the Knoop hardness (HK) is calculated based on the measurement of the long diagonal only and calculation of the projected area of the indent rather than the surface area of the indent:

$$HK = 14.229\left(\frac{F}{D^2}\right)$$

Where

HK = The Knoop hardness number ….. (3)

F = the applied load in kilograms - force

D^2 = the area of the indentation measured in square millimetres

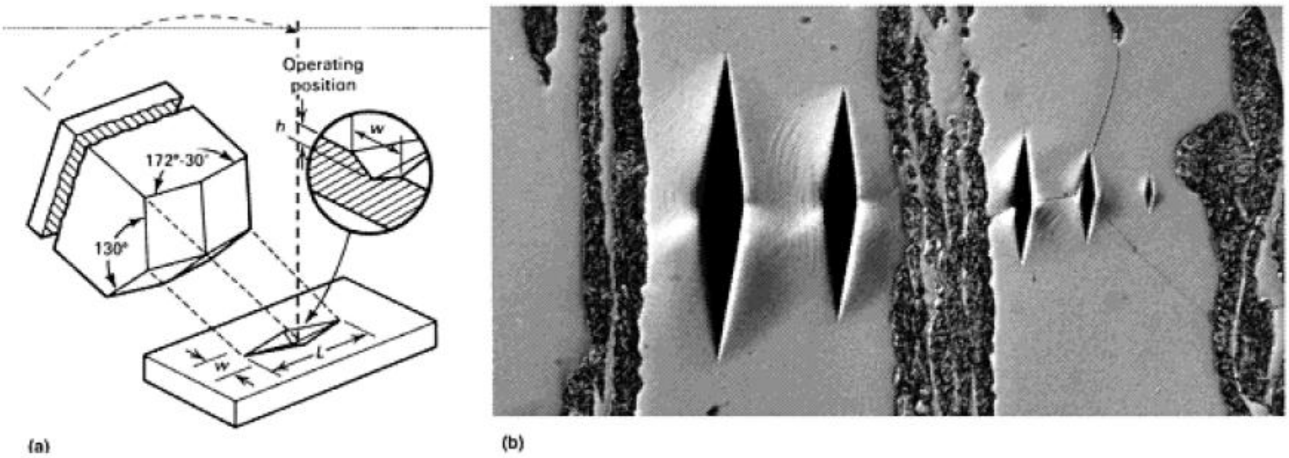


Fig. 5 Knoop hardness test. (a) Schematic of the rhombohedral-shaped diamond indenter used for the Knoop test and an example of the indentation it produces. (b) Knoop indents

A comparison for the most common hardness measures are shown by figure 4. Figure 5 (a) depicts a correlation chart of Vickers hardness (10 kgf load) to Knoop hardness at loads of 10, 25, 50, 100, 200. Figure 5 (b) and 500 gf, and conversions from Knoop hardness, with loads of 15, 25, 50, 100, 200, 300, 500, and

1000 gf, to Rockwell C. A general comparison of indentation hardness testing methods, including ultrasonic, is given in Table 1.

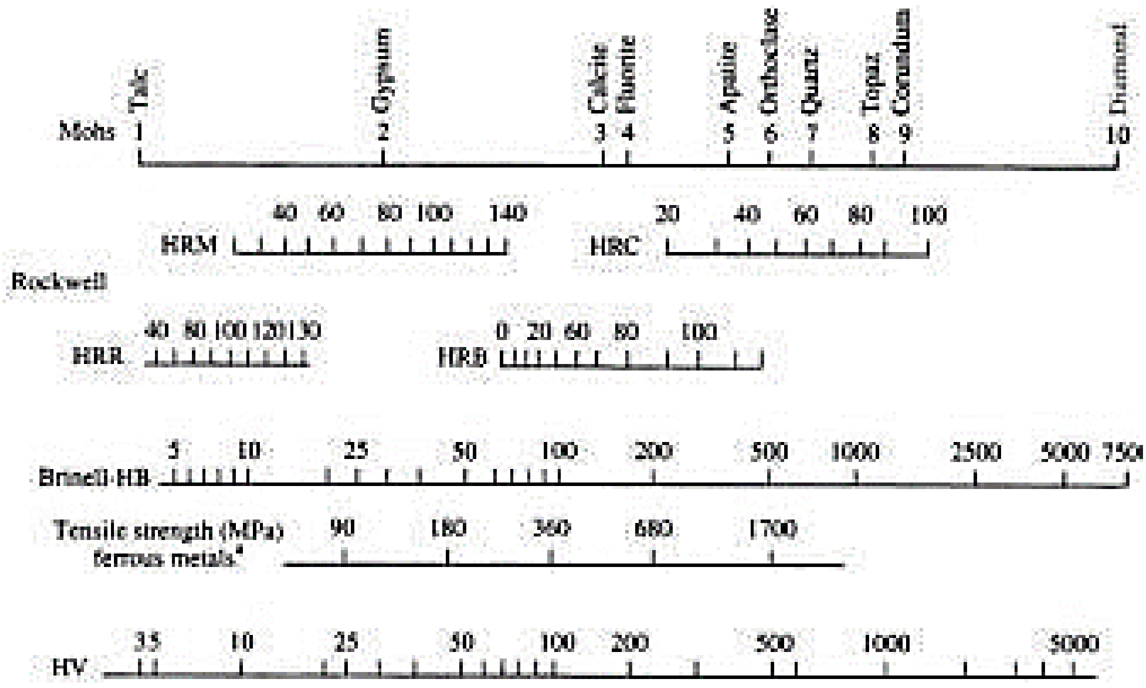


Figure 4. Comparison between variant hardness Measures

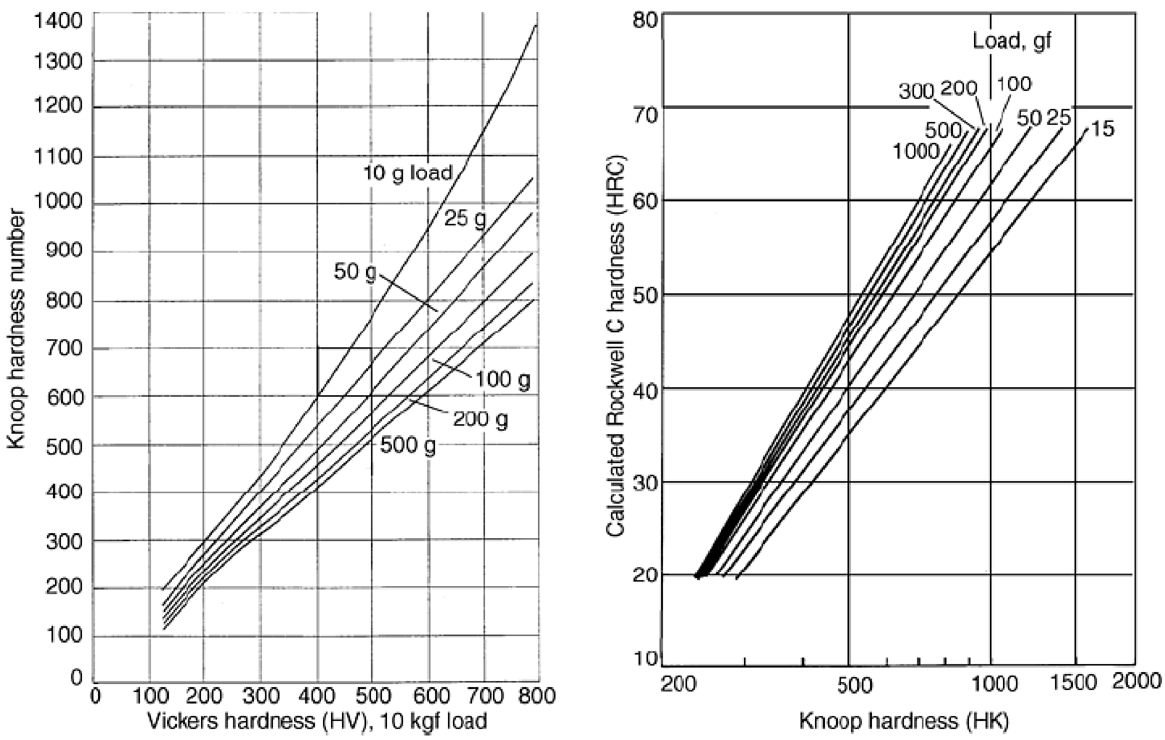


Fig. 5 (a) Correlations between Vickers hardness determined with a 10 kgf load and Knoop hardness determined with loads from 10-500 gf. (b) Correlations between Knoop hardness at loads form 15-1000 gf and Rockwell C hardness.

Table 3 Comparison of indentation hardness tests

Test	Indenter(s)	Indent		Load(s)	Method of measurement	Surface preparation	Tests per hour	Applications	Remarks
		Diagonal or diameter	Depth						
Brinell	Ball indenter, 10 mm (0.4 in.) or 2.5 mm (0.1 in.) in diameter	1–7 mm (0.04–0.28 in.)	Up to 0.3 mm (0.01 in.) and 1 mm (0.04 in.), respectively, with 2.5 mm (0.1 in.) and 10 mm (0.4 in.) diam balls	3000 kgf for ferrous materials down to 100 kgf for soft metals	Measure diameter of indentation under microscope; read hardness from tables	Specially ground area for measurements of diameter	50 with diameter measurements	Large forged and cast parts	**Damage to specimen minimized by use of lightly loaded ball indenter. Indent then less than Rockwell**
Rockwell	120° diamond cone, 1.6–13 mm ($\frac{1}{16}$ to $\frac{1}{2}$ in.) diam ball	0.1–1.5 mm (0.004–0.06 in.)	25–375 μm (0.1–1.48 μin.)	Major 60–150 kgf Minor 10 kgf	Read hardness directly from meter or digital display	No preparation necessary on many surfaces	300 manually 900 automatically	Forgings, castings, roughly machined parts	**Measure depth of penetration, not diameter**
Rockwell superficial	As for Rockwell	0.1–0.7 mm (0.004–0.03 in.)	10–110 μm (0.04–0.43 μin.)	Major 15–45 kgf Minor 3 kgf	As for Rockwell	Machined surface, ground	As for Rockwell	Critical surfaces of finished parts	**A surface test of case hardening and annealing**
Vickers	136° diamond pyramid	Measure diagonal, not diameter	30–100 μm (0.12–0.4 μin.)	1–120 kgf	Measure indent with low-power microscope; read hardness from tables	Smooth clean surface, symmetrical if not flat	Up to 180	Fine finished surfaces, thin specimens	**Small indent but high local stresses**

8. Hardness vs. Hardenability

Hardenability describes how deep the steel may be hardened upon quenching from high temperature. The depth of hardening is an important factor in a steel part's toughness. Hardenability is the ability of a steel to achieve a certain hardness at a given depth, upon suitable heat treatment and quench. Hardness can be measured in steels in any condition. Hardenability presumes that the steels will be heat treated to achieve a targeted hardness at a given depth. In the Jominy test of hardenability, a standard specimen is heated then water quenched from the end, and a series of Rockwell hardness tests are taken in 1/16th inch increments along the length of the specimen, see figure 5.

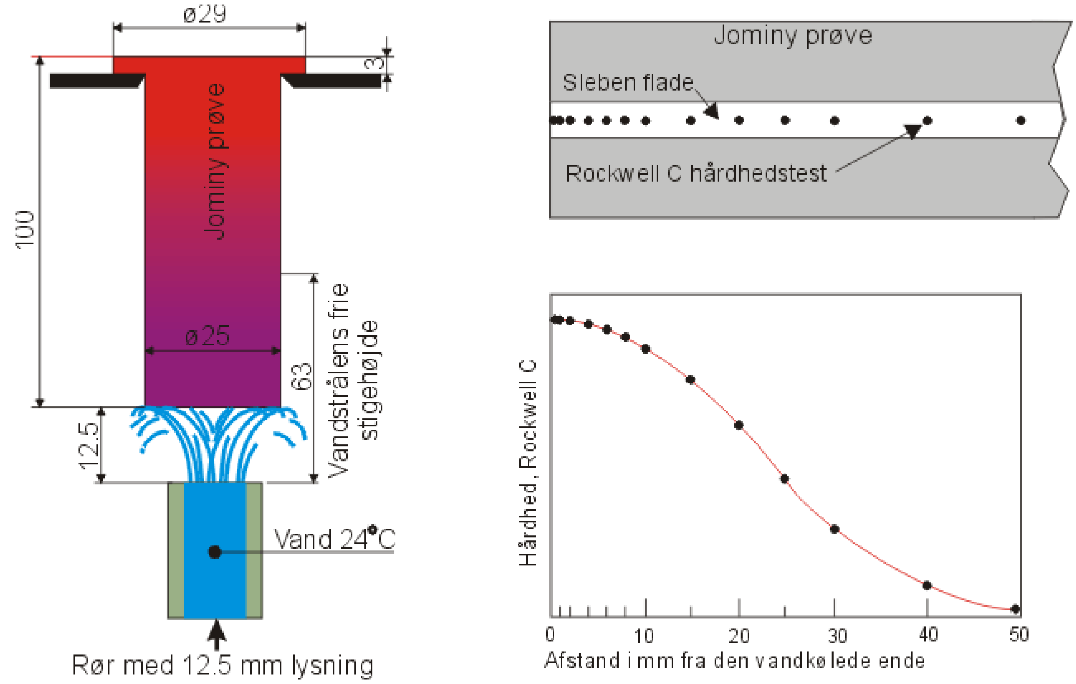


Figure 5. Jominy test of hardenability

9. Tools and Equipment.

The following Equipment, tools, and materials will be used during the experimental part of this experiment;

1. Hardness testing device(s)
2. Metallic Samples to be tested

10. Requirements.

1. Students should test and evaluate and discuss hardness of different metals samples in the Lab using the available apparatus, consequently they should submit within one week a Lab report.
2. Students should explain the terms; macro-, micro- or nano- scale hardness measurement?
3. Students should discuss the variant ways that can be applied for hardness testing, give examples?
4. Students should discuss hardenability

11. References

[1] Harry Chandler, (1999). Hardness Testing, ASM International, 2nd Edition, ISBN: 978-0-87170-640-9.

[2] Ref: http://www.mee-inc.com/microhar.html

[3] ASM Handbook, (2000). Mechanical Testing and Evaluation, Vol. 8. ASM International.