

Objective

The main objective of this experiment is to introduce two important basic mechanical property tests; hardness (using Rockwell testing) and impact (using Charpy testing). Chauvenet's Criterion will be applied to identify outliers and probability paper will be used to ascertain whether or not the repeated measure hardness data is normally distributed.

Abstract

The mechanical properties of materials are ascertained by performing carefully designed laboratory experiments that replicate, as nearly as practical, the service conditions. Factors to be considered include the nature of the applied load(s), its' duration and the applicable environmental conditions. It is possible for the load to be tensile, compressive, or shear, and its magnitude may be constant with time, or it may fluctuate continuously. Application time may be for only a fraction of a second, or it may extend over a period of many years. Service temperature can also be an important factor.

Mechanical properties are of concern to a variety of parties (e.g., producers and material consumers, research organizations and government agencies) that have differing interests. Consequently, it is imperative that there be some consistency in the manner in which tests are conducted, and in the interpretation of their results. This consistency is accomplished by using standardized testing techniques. Establishment and publication of these standards are often coordinated by professional societies. In the United States the most active organization is the American Society for Testing and Materials (ASTM); its Annual Book of ASTM Standards comprises numerous volumes that are updated yearly. A large number of the ASTM Standards are relate directly to mechanical testing techniques including specifications for measuring the hardness and impact properties of materials.

Background – Impact Testing

Toughness is a measure of the amount of energy a material can absorb before fracturing. It becomes of engineering importance when the ability of a material to withstand an impact load without fracturing is considered. Impact test conditions were chosen to represent those most severe relative to the potential for fracture, namely, (1) deformation at a relatively low temperature, (2) a high strain rate (i.e., rate of deformation), and (3) a triaxial stress state (which may be introduced by the presence of a notch).

Two standardized tests, the Charpy and Izod, are commonly used to measure Impact Energy (sometimes referred to as Notch Toughness). The Charpy V-notch (CVN) technique is most commonly used in the United States. For both Charpy and Izod, a V-notch is machined into a bar specimen with a square cross-section. A standard V-notch test apparatus is schematically illustrated in Figure 1. The load is applied as an impact blow from a weighted pendulum hammer that is released from a cocked position at a fixed height "h". The specimen is positioned at the base as shown. Upon release, a knife edge mounted on the pendulum strikes and fractures the specimen at the notch, which acts as a point of stress concentration for the high velocity impact blow. The pendulum continues its swing, rising to a maximum height "h'", which is lower than "h". Based on the difference between h and h', the energy absorption of the specimen is computed. The primary difference between the Charpy and Izod techniques lies in the manner of specimen support as is indicated in Figure 4. Variables including specimen size and shape, as well as notch configuration and depth can influence the test results.

Rolfe and Barsom (1987) developed a correlation between CVN and Fracture Toughness (K_{Ic}) that is given by:

$$\left(\frac{K_{Ic}}{\sigma_{ys}} \right)^2 = 5 \left(\frac{CVN}{\sigma_{ys}} - 0.05 \right)$$

Where K_{Ic} is the fracture toughness at slow loading rates ($\text{ksi}(\text{in})^{1/2}$), σ_{ys} is the **0.2%** offset yield strength (ksi), and **CVN** is the standard Charpy V-Notch impact test value.

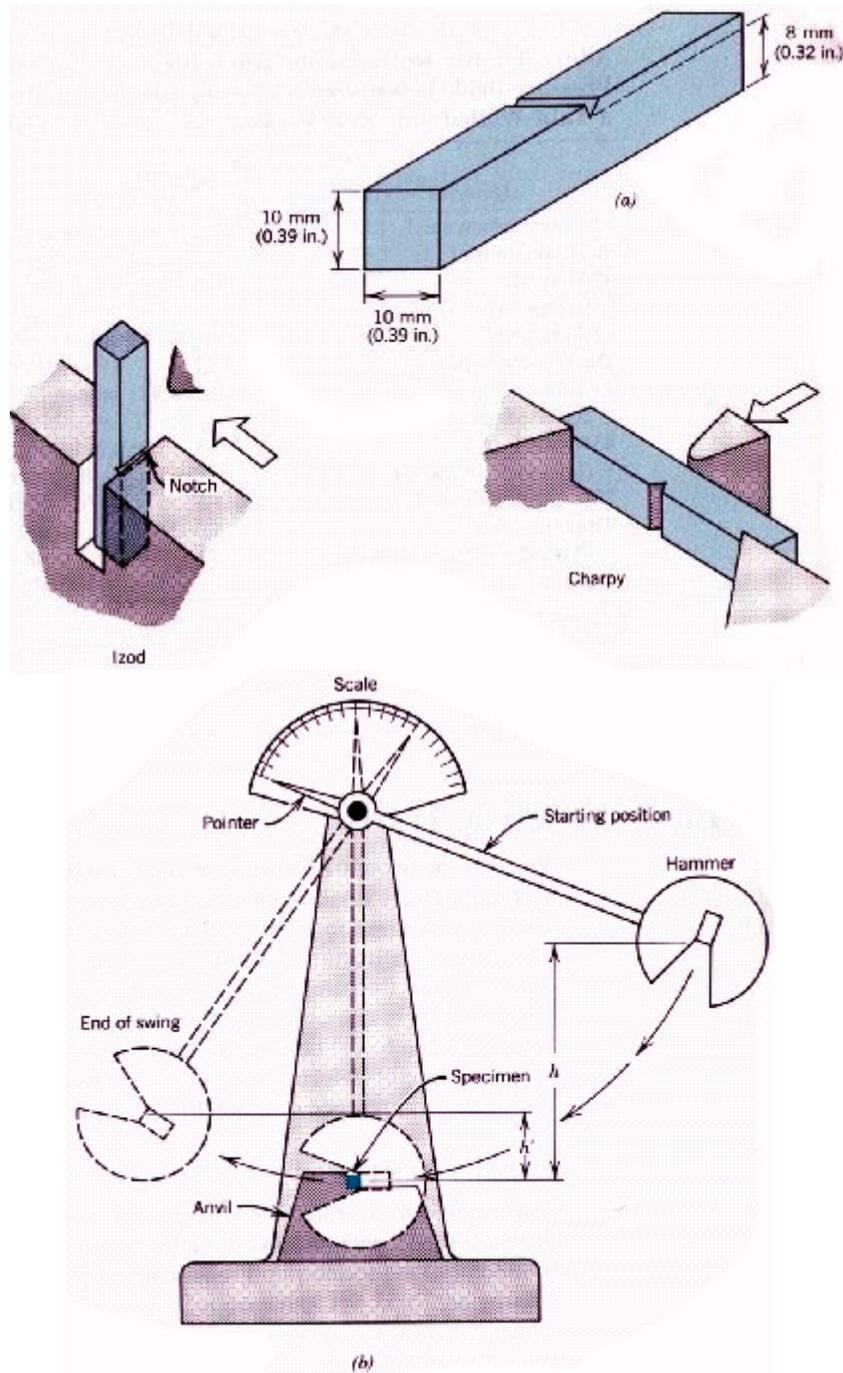


Figure 1(a) and 1 (b) – Schematic Drawing of a Standard Impact-Testing Apparatus. [Callister, 1991]

Background - Statistical Considerations

Chauvenet's Criterion

Engineers often find that some data points look bad and out of place in comparison with the bulk of the data in a set of repeated measures data. When this occurs, the engineer must decide if outlying data points are experimental blunders, and hence may be neglected, or if they represent some new type of physical phenomenon that is peculiar to a certain operating condition. The engineer cannot just ignore those points that do not fit with expectations, thus Chauvenet developed a criterion to determine whether or not suspect data points can be eliminated from the analysis (points may be eliminated from the analysis but should never be eliminated from the data set!).

Suppose "n" measurements of a quantity are taken and "n" is large enough that we may expect the results to follow a Gaussian (Normal) Error Distribution. This distribution may be used to compute the probability that a given reading will deviate a certain amount from the mean. A probability much smaller than 1/n is very unlikely to occur in a set of "n" measurements. Chauvenet's criterion specifies that a reading may be rejected if the probability of obtaining the particular deviation from the mean is less than 1/(2n.). Table 1 lists values of the ratio of mean deviation to standard deviation for various values of "n" according to this criterion.

In applying Chauvenet's criterion to consider the elimination of suspect data points, one first calculates the mean value and standard deviation using all of the collected data points. The deviations of the individual points from the mean are then compared with the standard deviation in accordance with the information in Table 3. If the critical value is exceeded then the data points in question are eliminated from the analysis. For the final data presentation, a new mean value and standard deviation are computed with the rejected data points eliminated. Note that Chauvenet's criterion might be applied a second or third time to eliminate additional points, but this practice is unacceptable, and only the first application may be used.

Table 1 - Chauvenet's Criterion For Rejecting A Reading

Number of readings, <i>n</i>	Ratio of maximum acceptable mean deviation to standard deviation, d_{max}/s
2	1.15
3	1.38
4	1.54
5	1.65
6	1.73
7	1.80
10	1.96
15	2.13
25	2.33
50	2.57
100	2.81
300	3.14
500	3.29
1,000	3.48

Normal Distribution – Probability Paper

To determine whether a data set follows a Gaussian distribution, Probability Paper is often utilized. Probability Paper uses the coordinate system where the ordinate (Y axis) has the percent of readings at or below the value of the abscissa (X axis) which is the value of a particular reading. The data must be Rank-Ordered prior to plotting and the largest value cannot be plotted because the Y-axis does not extend to 100%. The X-axis spacings are such that Normally Distributed Data (Gaussian) will plot as a straight line; thus if the plotted data is approximately linear when plotted on probability paper, then the data can be said to be normally distributed. The upper and lower ends of the curve are less important than the center portion in determining the adequacy of the Normally Distributed assumption.

Example 1: The following length data were collected for the measurement of the length of a single steel rod. Apply Chauvenet's Criterion to determine if suspect data points can be eliminated, plot the data on probability paper, and comment on the normality of the distribution.

Reading	$X_i, \text{ cm}$
1	4.64
2	4.63
3	4.37
4	4.66
5	4.61
6	4.65
7	4.59
8	4.69
9	4.70
10	4.68

The mean of the data set is given by:

$$\bar{x} = \frac{1}{10} \sum X_i = \frac{1}{10}(46.22) = 4.622 \text{ cm}$$

Sample standard deviation can be computed as:

$$S = \left(\frac{1}{n-1} \sum (X_i - X_m)^2 \right)^{1/2} = 0.09508 \text{ cm}$$

The following table presents the data in Rank Order, the Mean Deviations (d_i) and the ratio of the mean deviations to the standard deviation:

Rank Order	$X_i \text{ (cm)}$	$ d_i $	$ d_i /s$	Chauvenet's Criterion
1	4.37	0.252	2.6504	Reject
2	4.59	0.032	0.3365	Accept
3	4.61	0.012	0.1262	Accept
4	4.63	0.008	0.0841	Accept
5	4.64	0.018	0.1893	Accept
6	4.65	0.028	0.2945	Accept
7	4.66	0.038	0.3997	Accept
8	4.68	0.058	0.6100	Accept
9	4.69	0.068	0.7152	Accept
10	4.70	0.0780	0.8204	Accept

"DO NOT ELIMINATE THE DATA POINT FROM THE DATA SHEET"!!!

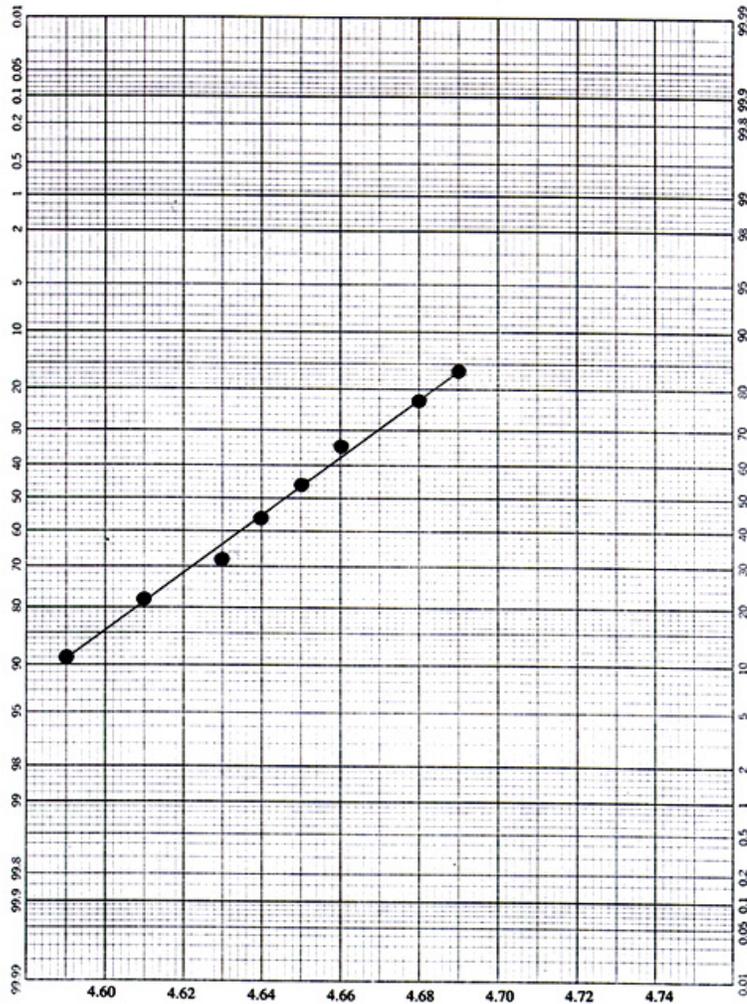
Since d_{max} / S for the ten readings is 1.96 (see Table 1), the first data point can be eliminated from the data analysis, but to determine whether or not the data is Normally (Gaussian) Distributed, the data should now be tabulated in rank order with appropriate cumulative percentages and the rejected data points not included: (*Since there are now only 9 data points, the % Below X_i will be in increments of $1/9 \times 100$ or 11.11%)

Rank Order	X_i (cm)	% Below X_i
1	4.59	11.11
2	4.61	22.22
3	4.63	33.33
4	4.64	44.44
5	4.65	55.55
6	4.66	66.66
7	4.68	77.77
8	4.69	88.88
9	4.70	99.99

The data are now plotted on Probability Paper as shown below to evaluate the Normality of the data. The mean value of the revised data set, without the Chauvenet rejected data points included, should now be computed. For this problem,

$$X_{REV} = 4.650 \text{ cm,}$$

if the data is Normally Distributed then an approximately linear fit should pass through 50% very near 4.650 cm (see Figure 5). One would conclude that the data appears to be linearly distributed based on the probability plot shown in Figure 5.



Rod Length, X_i (cm)

Figure 2 – Example Data Plotted on Probability Paper.

Background - Hardness Testing

Hardness is a measure of a material's resistance to localized plastic deformation (e.g., a small dent or scratch). Hardness testing involves a small indenter being forced into the surface of the material being 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. Measured hardnesses are only relative (rather than absolute) thus care must be taken when comparing values determined by different techniques.

Macro-Hardness (Rockwell and Brinell) testing is the most commonly applied materials test in industry due to several factors:

- 1) Macro-Hardness Testing is simple to perform and does not require highly skilled operators;
- 2) Through the use of different loads and indenters, hardness testing can be used for determining the hardness and approximate strength of most metals and alloys including soft bearing materials and high-strength steels;
- 3) Hardness readings can be taken in a few seconds with minimal preparation; and
- 4) For Rockwell hardness testing, no optical measurements are required; all readings are direct.

There are two common methods applied to measure material hardness macroscopically: Rockwell and Brinell. Rockwell hardness differs from Brinell hardness testing in that the indentation size is measured in Brinell testing while Rockwell hardness is determined by the depth of the indentation made by a constant applied load. For thin test samples or samples for which the relatively large Brinell or Rockwell indentations must be avoided, the Superficial Rockwell hardness test is often employed. Superficial Rockwell hardness testing employs lower loads to the indenter in order to minimize penetration.

The **Rockwell Hardness Test** consists of measuring the additional depth to which an indenter is forced by a heavy (major) load beyond the depth of a previously applied light (minor) load as illustrated in Figures 6 and 7. Application of the minor load eliminates backlash in the load train and causes the indenter to break through slight surface roughness and to crush particles of foreign matter, thus contributing to much greater accuracy in the test.

The minor load is applied first, and a reference or "set" position is established on the measuring device or the Rockwell hardness tester. Then the major load is applied at a prescribed, controlled rate. Without moving the workpiece being tested, the major load is removed and the Rockwell hardness number is indicated on the dial gage. The entire operation takes from 5 to 10 seconds.

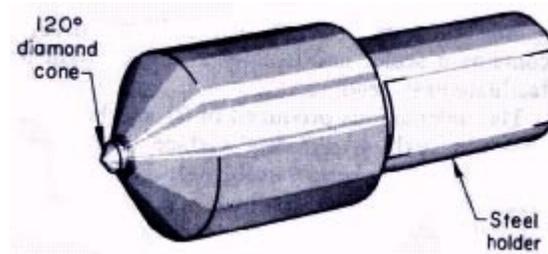


Figure 3 – Diamond-Cone Brale Indenter used in Rockwell Hardness Testing (2X). [Metals Hdbk, 1992]

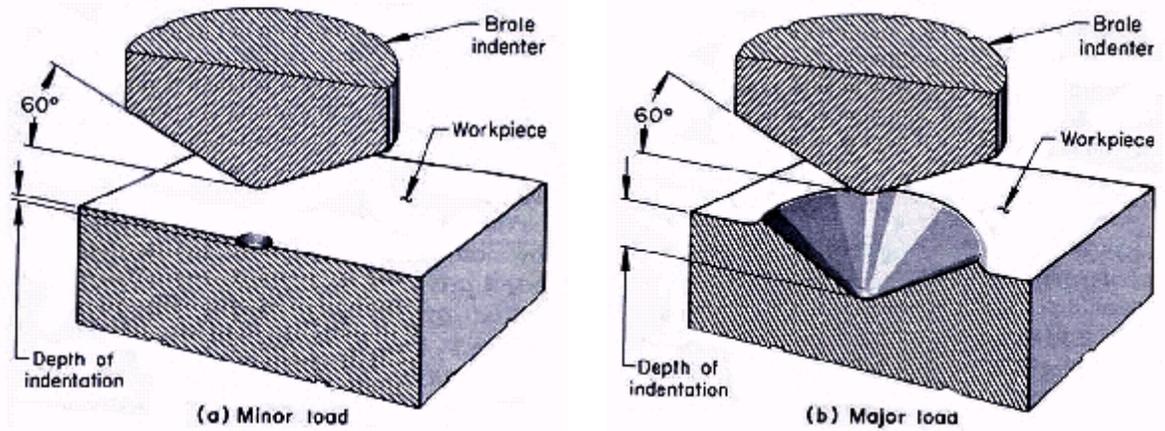


Figure 4 – Indentation in a workpiece made by application of (a) the minor load, and (b) the major load, on a diamond Brale indenter in Rockwell hardness testing. [Metals Hdbk - Desk Edition, 1992].

Hardness value based on the difference in depths of indentation produced by minor and major load. Diamond indenters are used mainly for testing materials such as hardened steels and cemented carbides. Steel-ball indenters, available with diameters of 1/16, 1/8, 1/4 and 1/2 in., are generally used for testing materials such as soft steel, copper alloys, aluminum alloys and bearings metals. Designations and typical applications of various indenters are listed in Tables 2 and 3.

Table 2 – Rockwell Hardness Scale Designations for Combinations of Type of Indenter and Major Load. [Metals Handbook - Desk Edition, 1992]

Table 1. Rockwell-hardness-scale designations for combinations of type of indenter and major load

Scale designation	Indenter		Major load, kg	Dial figure	Scale designation	Indenter		Major load, kg	
	Type	Diam. in.				Type	Diam. in.		
Regular Rockwell tester					Superficial Rockwell tester				
B	Ball	1/16	100	Red	15N	N Brale	...	15	
C	Brale	...	150	Black	30N	N Brale	...	30	
A	Brale	...	60	Black	45N	N Brale	...	45	
D	Brale	...	100	Black	15T	Ball	1/16	15	
E	Ball	1/8	100	Red	30T	Ball	1/16	30	
F	Ball	1/16	60	Red	45T	Ball	1/16	45	
G	Ball	1/16	150	Red	15W	Ball	1/8	15	
H	Ball	1/8	60	Red	30W	Ball	1/8	30	
K	Ball	1/8	150	Red	45W	Ball	1/8	45	
L	Ball	1/4	60	Red	15X	Ball	1/4	15	
M	Ball	1/4	100	Red	30X	Ball	1/4	30	
P	Ball	1/4	150	Red	45X	Ball	1/4	45	
R	Ball	1/2	60	Red	15Y	Ball	1/2	15	
S	Ball	1/2	100	Red	30Y	Ball	1/2	30	
V	Ball	1/2	150	Red	45Y	Ball	1/2	45	

Table 3 – Typical Applications of Regular Rockwell Hardness Scales. [Metals Handbook - Desk Edition, 1992]

Scale(a)	Typical applications
B	Copper alloys, soft steels, aluminum alloys, malleable iron
C	Steel, hard cast irons, pearlitic malleable iron, titanium, deep case-hardened steel and other materials harder than 100 HRB
A	Cemented carbides, thin steel and shallow case-hardened steel
D	Thin steel and medium case-hardened steel and pearlitic malleable iron
E	Cast iron, aluminum and magnesium alloys, bearing metals
F	Annealed copper alloys, thin soft sheet metals
G	Phosphor bronze, beryllium copper, malleable irons. Upper limit is 92 HRG, to avoid flattening of ball.
H	Aluminum, zinc, lead
K,L,M,P, R,S,V	Bearing metals and other very soft or thin materials. Use smallest ball and heaviest load that do not give anvil effect.

(a) The N scales of a superficial hardness tester are used for materials similar to those tested on the Rockwell C, A and D scales, but of thinner gage or case depth. The T scales are used for materials similar to those tested on the Rockwell B, F and G scales but of thinner gage. When minute indentations are required, a superficial hardness tester should be used. The W, X and Y scales are used for very soft materials.

The minor load is always 10 kg in regular Rockwell hardness testing. No Rockwell hardness value is expressed by a number alone. A letter has been assigned to each combination of load and indenter, as indicated in Tables 1 and 2. Each number is suffixed first by the letter H (for hardness), then the letter R (for Rockwell), and finally the letter that indicates the scale used. For example, a value of 60 in the Rockwell C scale is expressed as 60 HRC, etc. One Rockwell number represents an indentation of 0.002 mm (0.00008 in.).

Therefore a reading of 60 HRC indicates an indentation from minor to major load of $(100 - 60) \times 0.002 \text{ mm} = 0.080 \text{ mm}$ or 0.0032 in. A reading of 80 HRB indicates an indentation of $(130 - 80) \times 0.002 \text{ mm} = 0.100 \text{ mm}$.

The metal immediately surrounding the indentation from a Rockwell hardness test is cold worked thus multiple readings cannot be taken at the same point on a material's surface. If multiple tests are conducted on a single part the indentations should each be a minimum of 3 indentation diameters apart. The depth of material affected during testing is on the order of ten times the depth of the indentations.

Therefore, unless the thickness of the metal being tested is at least ten times the depth of the indentation, an accurate Rockwell hardness test cannot be expected. In addition to the limitation of indentation depth for a workpiece of given thickness and hardness, there is a limiting factor on the minimum material width. If the indentation is placed too close to the edge of a workpiece, the edge will deform outward and the Rockwell hardness number will be decreased accordingly. Experience has shown that the distance from the center of the indentation to the edge of the workpiece must be at least 3 times the diameter of the indentation to ensure an accurate test.

A fundamental requirement of the Rockwell hardness test is that the surface of the workpiece being tested be approximately normal to the indenter and that the workpiece must not move or slip in the slightest degree as the major load is applied. As one point of hardness represents a depth of only 0.0008 inches, a movement of only 0.001 inches could cause an error of over 10 Rockwell numbers. The support must be of sufficient rigidity to prevent its permanent deformation in use. Indenters are not calibrated below values of 20 or above values of 95, thus if readings are outside of this range then a different indenter must be selected. ⁹ Minimum thickness requirements, conversions between various Rockwell scales and round work corrections

are tabulated and are available in the Materials Testing Laboratory.

The **Brinell Hardness Test** consists of applying a constant load, usually 500 to 3000 kilograms, on a hardened steel ball-type indenter, 10 mm in diameter, to the flat surface of a workpiece. The 500-kilogram load is usually used for testing nonferrous metals such as copper and aluminum alloys, whereas the 3000-kilogram load is most often used for testing harder metals such as steels and cast irons. The load is held for a specified time (10 to 15 seconds for iron or steel and about 30 seconds for softer metals), after which the diameter of the recovered indentation is measured in millimeters. This time period is required to ensure that plastic flow of the work metal has stopped.

Brinell hardness is evaluated by taking the mean diameter of the indentation (two readings at right angles to each other) and calculating the Brinell hardness number (HB) by dividing the applied load by the surface area of the indentation according to the expression:

$$HB = L/(\pi D/2)[D - (D^2 - d^2)^{1/2}]$$

where L is the load in kilograms, D is the diameter of the ball in millimeters, and d is the diameter of the indentation in millimeters. Highly hardened steel (or other very hard metals) cannot be tested by a hardened steel ball by the Brinell method because the ball would plastically deform and flatten during penetration. Tungsten carbide balls are recommended for Brinell testing materials of hardness from 444 HB up to 627 HB (indentation of 2.45 mm in diameter). However, higher Brinell values will result when using carbide balls instead of steel balls because of the difference in elastic properties. The degree of accuracy that can be attained by the Brinell hardness test is greatly influenced by the surface smoothness and therefore the test surface should be filed, ground, machined or polished with emery paper such that the indentation diameter is clearly enough defined to permit its' accurate measurement.

General precautions of Brinell hardness testing include the following:

1. Indentations should not be made on a curved surface having a radius of less than 1 inch.
2. The load should be applied in such a way that the direction of loading and the test surface are perpendicular to each other within 2°.
3. The thickness of the workpiece being tested should be such that no bulge or mark showing the effect of the load appears on the side of the workpiece opposite the indentation. In any event, the thickness of the specimen shall be at least 10 times the depth of the indentation

The Brinell hardness test has three principal *limitations* as follows:

1. Size and shape of the workpiece must be capable of accommodating the relatively large indentations.
2. Because of the relatively large indentations, the workpiece may not be usable after testing.
3. The limit of hardness range -- about 11 HB with the 500-kg load to 627 with the 3000-kg load -- is generally considered the practical range.

Superficial Rockwell Hardness Testing employs a minor load of 3 kilograms, and a major load of 15, 30 or 45 kilograms. Just as in regular Rockwell testing, the indenter may be either a diamond brale or steel ball depending mainly on the ductility of the material being tested. Superficial Rockwell hardness values are always expressed with a number suffixed by a number and a letter that show the load/indenter combination. For example, if a load of 30 kg is used with a diamond indenter and a reading of 80 is obtained, the result is reported as 80 HR30N (where H indicates hardness, R indicates Rockwell, 30 indicates a major load of 30 kg, and N indicates the use of a diamond brale indenter).

All Superficial Rockwell hardness tests are started from the "Set" position. One Rockwell superficial hardness number represents an indentation of 0.001 mm or 0.00004 inches. Therefore, a reading of 80 HR30N indicates an indentation from minor to major load of (100 - 80) X 0.001 mm = 0.020 mm or 0.0008 inches. 10

Correlation between Hardness and Tensile Strength – Both tensile strength and hardness are indicators of a metal’s resistance to plastic deformation. Consequently, they are roughly proportional. As a rule of thumb for steels (steels only!), the HB and Tensile Strength are related according to

$$TS \text{ (MPa)} = 3.45 \times HB \text{ or } TS \text{ (psi)} = 500 \times HB.$$

A comparison/conversion between various hardness scales is provided as Figure 5.

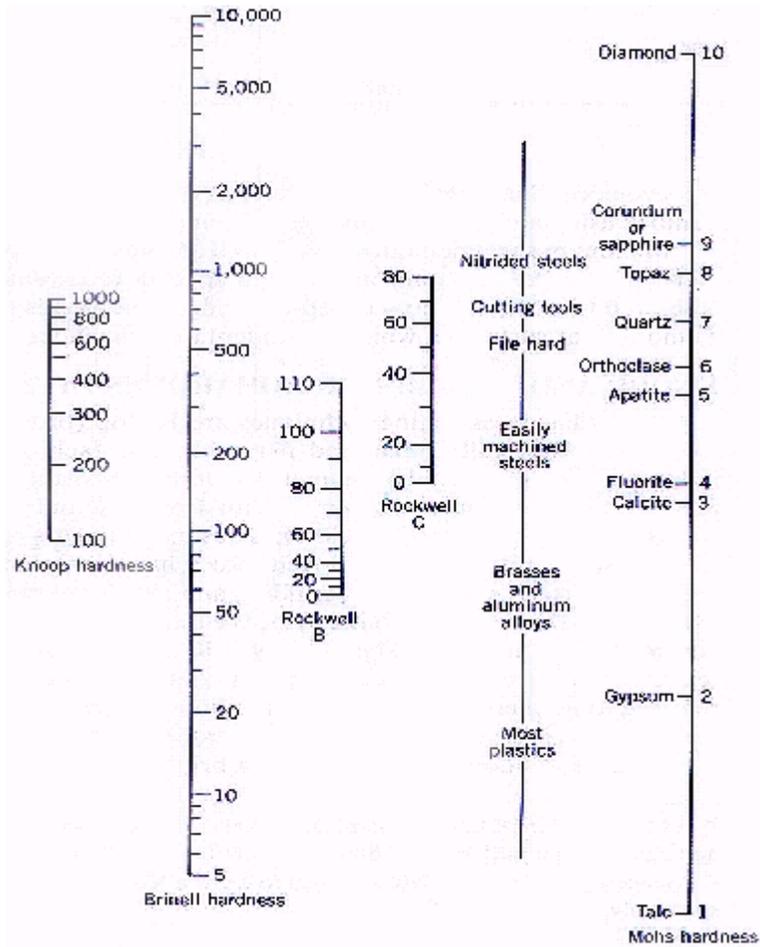


Figure 5 – Comparison of Several Hardness Scales. [Callister, 1991]

Lab Requirements

MacroHardness Testing

1. Each student will be given a sample for hardness testing. Working in groups of 2 students, make 20 Rockwell hardness measurements on the surface of each sample and record the results on the Data Sheet provided provided in this module. Remember to record the Rockwell Hardness Scale and Indentor used! Check the minimum thickness table to ensure that your sample is sufficiently thick for the scale and indentor chosen (see the Approximate Minimum Thickness Chart in the lab). If your sample is curved then adjust your data accordingly based on the Round Work Correction factors provided in the lab.
2. Determine the data set Mean and Standard Deviation.
3. Rank order the data then compute and tabulate the $|d_i|$ and $|d_i|/s$ values.
4. Apply Chauvenet's Criterion to the data set and briefly discuss the results.
5. Organize the data set in tabular form for determining whether or not the data is Normally (Gaussian) Distributed then plot the data on the Probability Paper provided. Discuss the results.
6. If applicable, approximate the Tensile Strength of your sample; if not applicable then explain why.
7. Would you suggest conducting Rockwell-Type hardness tests on Ceramic Materials? Why or why not?
8. Would you suggest conducting Rockwell-Type hardness tests on Polymeric Materials? Why or why not?

Impact Testing

1. Each lab section will conduct two standard Charpy impact tests on 1018 steel samples; one sample at room temperature and one below freezing (packed in dry ice).
2. Assuring that the broken sample is below freezing for each test, conduct 5 hardness tests on the low-temperature sample; record the results. Then conduct 5 hardness tests on the room-temperature sample; record the results. Compute the averages.
3. Approximate the Tensile Strength of each sample based on the results of step 2.; briefly discuss the results.
4. Briefly discuss why the impact energies of the two samples are different.
5. Qualitatively relate hardness to impact energy.
6. Examine the fracture surfaces of the failed Charpy samples and briefly describe the salient features of each.

Homework

1. Explain the difference between strength, hardness and toughness.
2. How should a Rockwell hardness reading of 63 be expressed if tested with the C scale?
3. Would you expect a deep hardness indentation to result in a high hardness number? Explain. Why isn't the diamond brale indenter used on copper alloys?
4. If 10 hardness tests were to be conducted on the same specimen, why would large errors result if the measurements were all made at the same point?
5. What is "Superficial Rockwell Hardness Testing" and when should it be used?
6. Determine the Tensile Strength of a steel sample with a Rockwell C reading of 63.
7. What is the primary difference between Charpy and Izod Impact Testing?
8. Why is Chauvenet' s Criterion applied to repeated measures test data?
9. Chauvenet's Criterion may justify removing data points from the analysis but not from the data set; why?
10. After repeated measures test data is properly plotted on Probability Paper, how does one determine if the data is Normally Distributed?