Hardness Testing

The most widely accepted definition for hardness is, "the ability of a material to resist permanent penetration" by a much harder body. The purpose of a hardness test is to determine the suitability of a material for its designed purpose and also to check the particular treatment the material has received. The ease of obtaining hardness measurements has made it the most common method of inspection for metals, particularly for ferrous alloys. There is a definite relationship between the hardness of a material and the tensile properties for ferrous alloys that have hardness values between 200 and 500 Brinell. The Brinell Hardness Number multiplied by 500 will give the approximate tensile strength; however, it should be emphasized that tensile values determined by hardness measurements are approximations only. The true tensile strength can only be determined by a tensile test. Nevertheless, many small machine and heat treating shops rely on the hardness test to determine approximate tensile strength values, because it is much cheaper than machining tensile bars and making tensile tests.

Types of Hardness Testing

Hardness testing can be divided into two groups: macrohardness testing and microhardness testing. Macrohardness testing refers to testing with loads equal to or over one kilogram; microhardness testing refers to testing with loads less than or equal to 1000 grams, or one kilogram. Brinell, Rockwell®, and Vickers are examples of macrohardness testers; Micro-Vickers and Knoop are examples of microhardness testers.

Brinell Hardness Tester

The theory of Brinell Hardness Testing was proposed by Dr. J.A. Brinell of Sweden around the turn of the century, whereby a predetermined static load is applied to the specimen through the indenter. The standard indenter is a 10 mm tungsten carbide ball, and the standard load is 3000 Kgf.

Today's Brinell tester is substantially improved over earlier models. Loads are applied and monitored electronically, and while many testers still require the user to measure the diameters of impressions with a hand-held microscope containing a scale graduated in millimeters, there are newer models which utilize a depth of impression measurement technique. These newer testers allow users to use lighter loads and smaller diameter indenters, expanding the number and types of materials that can be tested with this method.

Brinell Hardness test results are reported as XXX HBW. Previously, when the ball used for testing was made of steel, the result was reported as XXX HBS.

Brinell Hardness Testing is usually reserved for forgings, castings, heat-treated parts, gears, and cast iron when an overall hardness is desired. The large standard indenter ensures an impression will cover an area containing many grains and also gives a good indication of sub-surface characteristics.

The surface condition for Brinell testing is not critical; in fact, an as-ground surface is considered adequate. Although surface parallelism is not a critical factor, some control should be exercised to prevent the indenter from slipping when contact is made. The specimen must be thick enough that no anvil effect is observed; anvil effect is a slight bulge that will occur on the back side of a specimen if it is too thin. Care should be taken that indentations are not too near the surface or too close to each other, otherwise a fictitious reading will be obtained. If too near the surface, the surface will bulge outward; and if the indentations are too close, the work hardening effect (or deformation), of one indentation will affect the true results of the other. As a general rule, indentations should be separated by at least twice the diameter of an indentation. Brinell readings should not be taken in mounted samples without first grinding off the back of the mount to expose the back of the sample; mounting media will crush under heavy loads.

It should be noted that the indentation area is the actual surface area and not the projected area of the indentation.

Conversion charts have been established that list corresponding Brinell Hardness Numbers for varying indentation diameters and with varying loads, but the following formula shows how a hardness value is determined.

$$BHN = \frac{L}{\frac{\pi D}{2}(D - \sqrt{D^2 - d^2})}$$

where L = load applied in kilograms
D = diameter of ball indenter (mm)
d = diameter of the measured indentation (mm)

Rockwell-Type Hardness Tester

By far the most popular tester used is the Rockwell or Rockwell-type tester. If it were possible to count all the hardness measurements made in one day, the number of Rockwell tests would probably equal all the others put together, and there is a good reason for this. The Rockwell tester is the easiest to use and the hardness value is read directly on a digital display or an analog dial gauge. Other testers (Brinell, Vickers, or Knoop) rely on an optical system to measure the diameter, the diagonals, or the length of indentation. Another reason for the popularity of the Rockwell tester is its versatility. With the proper indenter and load, fifteen different scales can be used just with the standard Rockwell tester, plus an additional fifteen with the superficial tester. Together, the standard and superficial testers offer thirty scales and these scales permit testing over a wide range of hardnesses. The combination of a standard and superficial tester in one unit, commonly referred to as a "Twin Tester", makes an extremely versatile hardness tester.

Unlike the Brinell tester, where the hardness number has a mathematical relationship to the diameter of the indentation, the Rockwell measures the depth of penetration.

Although there are inaccuracies in depth measurements with other types of hardness testers, the Rockwell overcomes this by means of a minor load (10 kg for standard testers, 3 kg for superficial testers), being applied first then followed by a major load. The differential ratio of the major load to the minor load provides the basis for Rockwell testing, and when the major load is removed (but not the minor load), the hardness value is read directly. Major loads are 60, 100, and 150 kg for the standard tester; and 15, 30, and 45 kg for the superficial tester. The Rockwell tester offers extreme versatility over a wide range of hardnesses. The indenters which are most frequently used on the standard tester are the spheroconical diamond indenter, used for the C scale and 150 kg load; and the 1/16-inch tungsten carbide ball indenter, used with the BW scale and 100 kg load. With the superficial hardness tester, the N and TW scales are more frequently used with loads of 30 and 45 kg. Following is a table listing the various standard scales, the loads used, and the use for the various scales.

Typical Application of Rockwell Scales

Scale	Indenter	Load (kg)	Application
BW	1/16-inch Carbide Ball	100	Unhardened carbon steel, copper and aluminum alloys, malleable iron
C	Diamond	150	Steel, hardened steel, case-hardened steels, pearlitic cast iron, titanium, and other materials harder than B100
A	Diamond	60	Cemented carbides, thin case-hardened parts, thin gauge steel
D	Diamond	100	Thin steel sheet material, medium case-hardened parts
EW	1/8-inch Carbide Ball	100	Cast iron, bearing material, aluminum, and magnesium alloys
FW	1/16-inch Carbide Ball	60	Thin, soft steel material, annealed copper alloys
GW	1/16-inch Carbide Ball	150	Malleable irons, phosphur bronze, beryllium copper
HW	1/8-inch Carbide Ball	60	Aluminum, lead, and zinc
KW	1/4-inch Carbide Ball	150	Babbitt material, lead-tin alloys, graphite, bearing material, very soft and thin material
LW	1/4-inch Carbide Ball	60	
MW	1/4-inch Carbide Ball	100	
PW	1/4-inch Carbide Ball	150	
RW	1/2-inch Carbide Ball	60	
SW	1/2-inch Carbide Ball	100	
VW	1/2-inch Carbide Ball	150	

The superficial scales are as follows.

Major Load	Scales				
	N	TW*	WW*	XW*	YW*
(kg)	Diamond	1/16-in. Ball	1/8-in. Ball	1/4-in. Ball	1/2-in. Ball
15	15	15	15	15	15
30	30	30	30	30	30
45	45	45	45	45	45

*Carbide Ball

The diamond and ball indenters used for superficial hardness measurements are the same that are used on the standard Rockwell tester, and are used for very thin gauge material requiring shallow indentations, thin carburized or nitrided surfaces, or small intricately shaped material that would collapse under the heavier loads of the standard tester. Even though the indenters used for the superficial scales are the same as used with the regular scales, an indenter should be dedicated to a particular scale. In other words an N indenter (diamond) should be used only for the N scale, C indenter for the C scale, etc.

The choice between standard and superficial testing is determined rather quickly, usually by the thickness of the material, but then there is the choice of which scale to use. Knowing the alloy and the condition it is in will narrow the choice considerably. In the majority of cases the choice will be between the BW and C scales on the standard tester, and between the N and TW scales for the superficial.

On Rockwell testers with digitally displayed hardness values, the use of the diamond indenter will cause the corresponding 0 set to register 100 on the display panel before the major load is applied. For ball indenter testing, the 0 set will register 130 before the major load is applied.

Although there is an overlap of hardness values on all the scales, Rockwell C testing below 20 is not recommended, nor is Rockwell BW testing above 100. If Rockwell C readings are below 20, the diamond indenter is pushed so far into the material that the shank of the indenter can be engaged in the material and cause invalid readings. Conversely, with Rockwell BW readings greater than 100, only a slight portion of the ball indenter is engaged in the material and poor sensitivity is the result. If Rockwell C readings are below 20, some other scale should be selected, the BW scale for instance. For Rockwell BW readings greater than 100, the next heavier load is selected, usually the C scale.

The surface condition of specimens for Rockwell testing is somewhat more critical than for Brinell testing. The surfaces should have a fine grind, 180 to 240 SiC, and be free of dirt, debris, and oil. The underside should be free of an oxide layer that could crush when the major load is applied, and some degree of parallelism should be present. The presence of oil on specimen surfaces can cause low readings.

Rockwell testing should not be performed on mounted samples without first grinding away the back of the mount to expose the back of the specimen. The resiliency of mounting media will cause low readings.

Every Rockwell tester should have a complete set of standard hardness test blocks. Daily checking with test blocks will indicate if the tester is in calibration or if an indenter is damaged. For instance, if the C scale is used throughout its range, the tester should be checked with the high, medium, and low test blocks, (usually 63, 45, and 25 Rockwell C). The same applies for the other scales.

Spacing of indentations should be between two or three center-to-center indentation distances apart to avoid invalid readings caused by the deformation around close indentations. Also, the anvil effect is to be avoided. Stacking thin gauge material one on top of another to avoid the anvil effect is not permited because of slippage between the contact surfaces. The only exception to this is when testing the hardness of plastics.

Vickers Hardness Test

There are two hardness tests that are called Vickers. One is an English Vickers test that works somewhat on the principle of the Brinell hardness tester, and falls into the category of macrohardness testing in that it uses loads over one kilogram. It uses a square-based diamond pyramid indenter and the hardness values are reported as Diamond Pyramidal Hardnesses (DPH). The other Vickers is a microhardness test, and the Vickers indenter is interchangeable with a Knoop indenter on the same microhardness tester.

To avoid confusion, the use of the Vickers in the remaining text will refer to microhardness testing with loads equal to or less than 1000 grams.

The diamond indenter used for Vickers hardness testing is an indenter ground in the shape of a square-based pyramid with an angle of 136 degrees between faces. The depth of a Vickers microindentation is about 1/7 of the length of the diagonal, and when measuring a microindentation, both diagonals should be measured and averaged. The Vickers Hardness Number is the ratio of the load applied to the indenter to the surface area of the microindentation. Although conversion charts are available, the following formula may be useful.

$$\text{VHN (DPH)} = \frac{2L \sin\frac{\theta}{2}}{d^2}$$

where L = load applied in kilograms

θ = angle of 136°

d = mean diagonal (mm)

however, $\sin\frac{\theta}{2} = 1.8544$

and a simplified formula is

$$\text{VHN} = \frac{1.8544 \times L\ (\text{kg})}{d^2\ (\text{mm})}$$

Knoop Hardness Tests

While the Vickers-type indenter is accepted worldwide, the Knoop indenter was developed and is primarily used by industry in the United States.

The Knoop indenter is a diamond ground in the shape of a pyramid with one face approximately seven times the length of the other. The included longitudinal angle is 172°30', and the included transverse angle is 130°0'. The shape of a Knoop microindentation is an elongated diamond in the form of a rhomboid, and only the long axis is measured. The depth of penetration is approximately 1/30 of the long diagonal.

The Knoop Hardness Number is the ratio of load applied to the indenter to the unrecovered projected area of the microindentation. Here is the formula.

$$KHN = \frac{L}{A} = \frac{L}{l^2 Cp}$$

where L = load applied in kilograms
A = the unrecovered projected area (mm^2)
l = length of long diagonal (mm)
Cp = constant, 0.07028 relating projected area of the microindentation to the square of the length of the long diagonal

The formula is usually shown as...

$$KHN = \frac{L\ (kg)}{l^2\ (mm) \times 0.07028}$$

Depth of Penetration

Calculating the depth of a hardness indentation can be of immense help in determining the load to be used, particularly in Vickers and Knoop microhardness testing, as well as the type of hardness test to be performed. The depth of a hardness indentation should not exceed 3/4 the thickness of the test piece. Usually the nominal thickness of the test piece is known, and placing a trial indentation and calculating the depth of penetration will indicate the load to be used.

The depth of a Brinell indentation is calculated as follows.

$$\text{Depth of Penetration} = \frac{L}{\pi DHB}$$

L = load (kg)
D = diameter of indentation (mm)
HB = hardness value

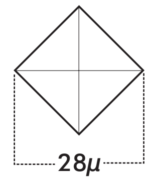
Depth of a Rockwell indentation is calculated as follows.

Diamond indenter, Regular scales	: 100 - hardness number x 0.002 mm
Diamond indenter, Superficial scales	: 100 - hardness number x 0.001 mm
Ball indenter, Regular scales	: 130 - hardness number x 0.002 mm
Ball indenter, Superficial scales	: 100 - hardness number x 0.001 mm

The depth of a Rockwell indentation so calculated is not measured from the surface of the sample to the bottom of the indentation, but rather is measured from the depth of penetration resulting from the application of the minor load, to the bottom of the indentation.

Determining the depths of Vickers and Knoop microindentation are best given as examples.

Assume a Vickers microindentation has an average diagonal measurement of 28 microns, then...

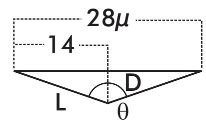


$$\sin\frac{\theta}{2} = \frac{14}{L} \qquad \sin\frac{\theta}{2} = 68°$$

$$\sin 68° = \frac{14}{L}$$

$$L = \frac{14}{\sin 68°} = \frac{14}{0.9272}$$

$$L = 15.1\mu$$



Given: Vickers Diagonal = 28μ
$\theta = 136°$
Determine: L (length) and D (depth)

$$\cos\frac{\theta}{2} = \frac{D}{L}$$

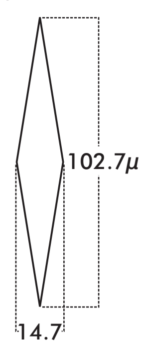
$$D = (\cos\frac{\theta}{2})(15.1)$$

$$D = (0.3746)(15.1)$$

$$D = 5.67\mu$$

Once L has been calculated, D (depth) can be determined by the Pythagorean Theorem or the law of tangents.

The depth of a Knoop microindentation is also best illustrated by an example; however, the width is measured and the included transverse angle of 130° must be used. Again, assume a Knoop microindentation measures 102.7 microns and the width is 14.7 microns, then...

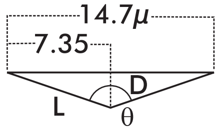


$$\sin\frac{\theta}{2} = \frac{7.35}{L} \qquad (\sin\frac{\theta}{2} = 65°)$$

$$\sin 65° = \frac{7.35}{L}$$

$$L = \frac{7.35}{\sin 65°} = \frac{7.35}{0.9063}$$

$$L = 8.11\mu$$



Given: length of microindentation = 102.7μ
width = 14.7
included transverse angle = 130°
Determine: L (length) and D (depth)

$$\cos\frac{\theta}{2} = \frac{D}{L} \qquad (\cos\frac{\theta}{2} = 65°)$$

$$\cos 65° = \frac{D}{L}$$

$$D = (\cos 65°)(8.11)$$

$$D = (0.4226)(8.11)$$

$$D = 3.43\mu$$

Again, once L has been calculated, D can be determined by the Pythagorean Theorem or the law of tangents.

Earlier, it was stated that the depth of a Vickers microindentation is approximately 1/7 of the measured diagonal and the Knoop microindentation is nearly 1/30 of the measured diagonal. In the case of Vickers, the depth of penetration is more like 1/5 and the Knoop is 1/30.

Proper Designations for Reporting Hardness Values

Hardness is not a property of a material. At best, hardness values are arbitrary and there are no absolute standards of hardness. Hardness values have no quantitative value unless expressed in terms of a given load applied in a specific manner and for a specific length of time. For example, a hardness value reported as 315 for a material is absolutely meaningless, but if the hardness value is reported as 315 HBW; 315 Vickers-10 kg load; or 315 Knoop-500 gm load; then the value is fully understood. Hardness values are usually reported with the following designations: 315 HBW means a Brinell Hardness Number of 315, and unless subscripted, it implies a 3000 kg load was used. If a different load was used (1500 or 500 kg) then it would be written 315 HBW_{1500}. Rockwell hardness values are expressed a little differently—60 HRC, 83 HRBW, 81 HR30N, or 70 HR45TW. The hardness is written first, and then the scale used; no subscripting is used. Vickers and Knoop hardness values are also similarly reported with the load applied subscripted—315 HK_{500}, 315 HV_{100}, etc.

Comparison of Vickers and Knoop Hardness Testing

The surface condition of specimens for microhardness testing using either the Vickers or Knoop indenters is critical. An as-polished surface is required, and one at least through a fine diamond compound polish. This is to ensure that the tips of the indentations can be sharply focused and measured. A specimen surface exhibiting many scratches would obliterate the tips, but more importantly, since microhardness testing uses light loads, surface anomalies will affect the hardness values. Parallelism is also a critical factor. The surface of the specimen must be completely normal to the indenter to insure a symmetrical microindentation. Indentations deviating by more than 5% for Vickers, or 10% for Knoop should be considered invalid. Deviations can be determined by measuring the opposite halves of indentations separately and obtaining the ratio by dividing the length of each half by the total length of the microindentation.

There are several means of establishing parallelism of a specimen. One is by using a self-leveling device that is available with microhardness testers; the other is to use a metal slide and a small wad of plasticine (modeling clay) that is placed between the metal slide and the bottom of the specimen, and a hand press. Protective paper such as lens tissue should be used between the hand press and specimen to protect the surface of the specimen. Unlike Brinell or Rockwell testers, microhardness tests can be performed on mounted specimens with no adverse effect.

As with other types of hardness testers, the spacing of indentations should be twice the distance of the width of a microindentation to avoid the effects of deformation. Even though a microindentation may not show strain or slip lines around it, deformation is present nevertheless.

If an overall hardness value is desired, Brinell or one of the Rockwell scales should be used. If hardness values are wanted on minor phases, grain boundary constituents, plated surfaces, diffusion zones, or if a hardness traverse is desired to determine the effective case depth of a carburized specimen, then a microhardness test should be used. In the latter illustration, a Knoop Hardness Traverse is preferred because more indentations can be placed in a given length.

Microhardnesses should be taken in the as-polished condition or, at the very most, lightly etched. Even normally etched microstructures can be too dark to see the tips of the indentations.

Since the Vickers indenter penetrates about twice as far as the Knoop indenter with a given load, the Vickers is less sensitive to surface conditions. On the other hand, because the indentations are shorter in length, it is more prone to errors in measuring.

Conversions from one Type of Hardness Test to Another

Everyone is more familiar with one type of hardness test than another and will try to "convert" one to the other for a better understanding. There are conversion charts available to make these conversions (for example, ASTM designation E-140, Standard Conversion Tables for Metals, Table 1); but **conversions are approximate** and not mathematically correct, and discretion is urged when using any conversion chart. The referenced conversion chart is probably the most used and lists comparable hardness values for the more popular hardness tests. It should be pointed out that this chart lists Diamond Pyramid Hardness, 10 kg, and this refers to the English Vickers Hardness Test mentioned earlier and not the Vickers hardness values obtained using a Vickers indenter with light loads on a microhardness tester. Also, the column headed by Knoop is for a load of 500 grams or over. A Knoop Hardness Number obtained with a load lighter than 500 grams cannot be converted to a comparable hardness value for other types of testers. Another type of conversion table is required to do this. This conversion chart (reproduced in Figure 1), was compiled by Lloyd Emond, and appeared in the Metals Progress approximately 40 or 50 years ago.

The chart is used in the following manner. Assume a Knoop hardness value of 500 is obtained using a 100 gram load and it is desired to convert this to a comparable Rockwell C value. Locate 500 Knoop value on the abscissa and read to the right until the 100 gram line is reached; drop straight down to the 500 gram line and read back to the abscissa. In this illustration 500 Knoop, 100 gram load is equivalent to approximately 450 Knoop, 500 gram load. This value can then be located on a conversion chart and the comparable Rockwell C value is 44. Another way to use the chart is to drop straight down to the ordinate (Vickers Hardness, 10 kg load) and then convert the equivalent Vickers value to Rockwell C. The Vickers Hardness values on the graph are again the English Vickers Hardnesses. It should be strongly emphasized that these conversions are approximations only, particularly when using the Knoop vs. Vickers conversion chart.

There is a close numerical agreement between Vickers and Knoop hardness values obtained with 500 and 1000 gram loads, but with loads less than 500 grams the numerical values become somewhat widely separated. This is known as Load Dependence. The graph shown in Figure 2 has been established showing the relationship, or conversions, between Vickers and Knoop hardness values using the same load. For example, the graph can be used to convert 400 HV_{50} to a comparable 460 HK_{50}, but if 400 HV_{50} is desired to be converted to an approximate HRC value, both the preceding graphs must be used. After the 400 HV_{50} has been converted to 460 HK_{50}, the first graph is used to convert 460 HK_{50} to a comparable 385 HK_{500}; then from a conversion chart this value is converted to an approximate 39 HRC value. By using three conversion charts, 400 HV_{50} has been converted to an approximate 39 HRC value. Again, caution is urged when converting in this manner, and it should be emphasized that **conversion values are approximations only**.

There is also good correlation when converting a 500 gram Knoop value to a comparable HRC or HRBW value when the microstructure is homogeneous. If the microstructure is heterogeneous, the specimen should be etched lightly to reveal different constituents that might want to be avoided when trying to obtain an overall hardness value.

One should always use the heaviest load possible when using microhardness testers. Usually, the lighter the load, the higher the hardness number (not value). If a specimen was tested with a 100 gram load and with a 500 gram load, the hardness number for the 100 gram load will be higher numerically. This is particularly true for Knoop Hardness numbers.

Various types of specimen holders are available to hold almost any morphology—holders for taking hardnesses on wires, both in the longitudinal and transverse directions; holders for ball bearings and universal holders that tilt are but a few that remove the tedium from microhardness testing.

The measuring eyepieces are extremely accurate, measuring to fractional micron values, and can be used for measuring plating thicknesses, length, and width of non-metallic inclusions, porosity, etc.

Automatic hardness testers are available that couple a microhardness tester with an automatic traversing stage and/or a video measuring system of varying degrees of automation. The operator places the specimen(s) on the stage and defines the desired pattern and number of impressions. The microindentations are made, measured, and a user-defined report is prepared. This report may contain conversions to other scales, along with statistical information, images of the test piece, and/or indentation patterns. This data can then be stored or shared as desired. Operator bias and subjectivity are entirely eliminated.

Macrohardness and microhardness testing are so related to metallography that a well equipped laboratory usually will have one type of each.

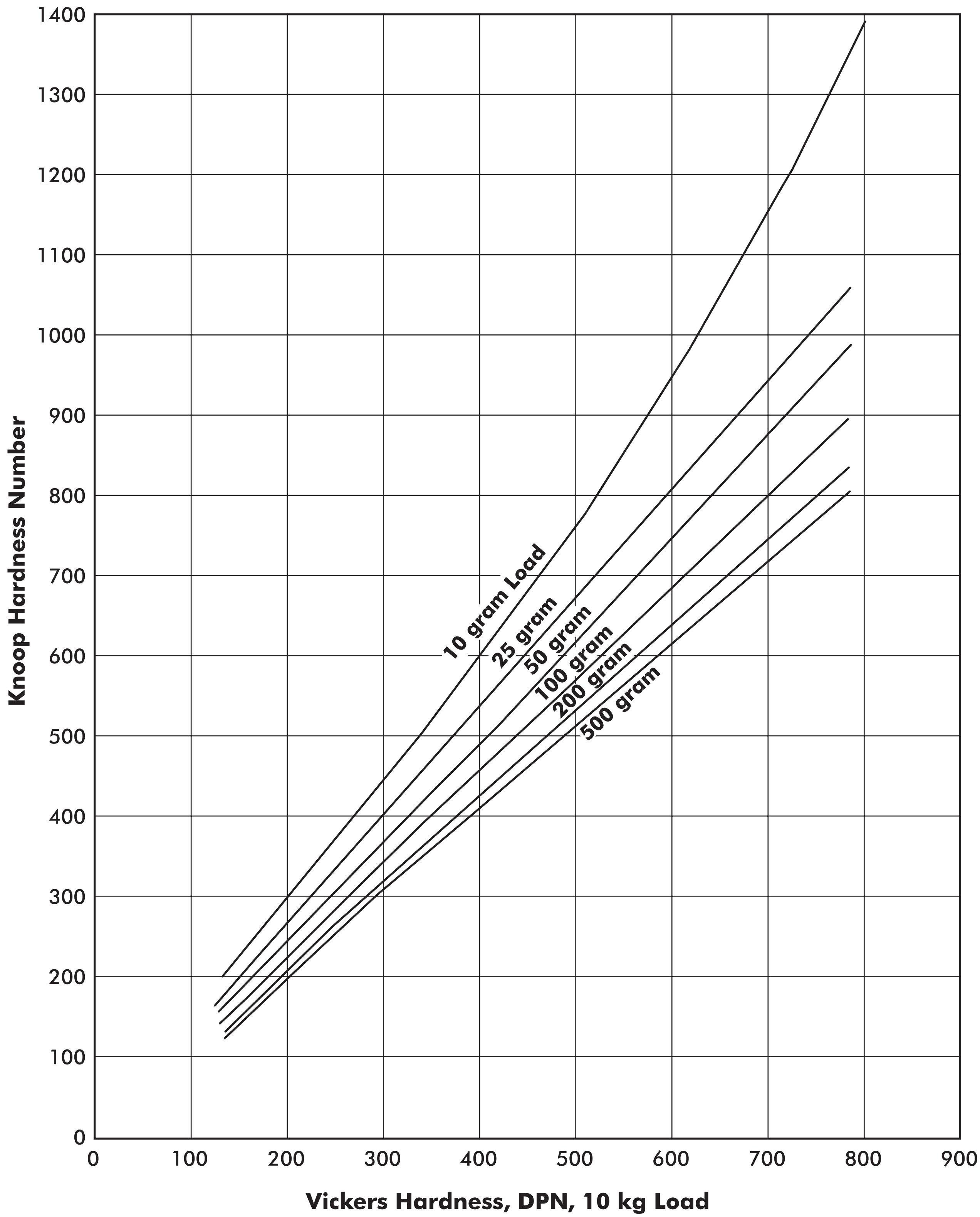


FIGURE 1. Knoop vs. Vickers, 10 kg load

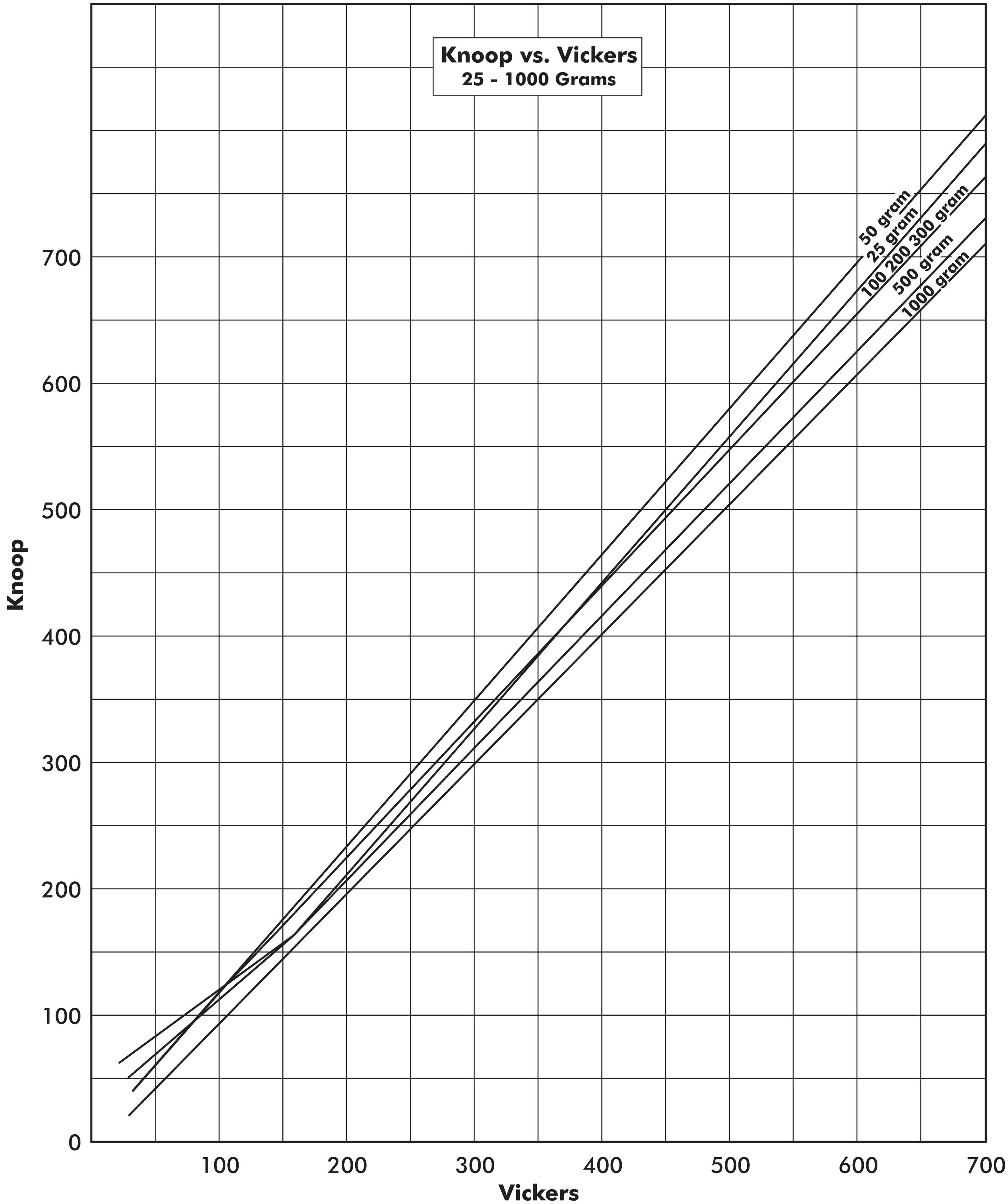


FIGURE 2. Knoop vs. Vickers

LECO Corporation would like to thank Dr. Lee Dillinger for his contributions to this project.

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