

MSE 528: Microhardness Hardness Measurements

Objectives:

- (1) To understand what hardness is, and how it can be used to determine material properties.
- (2) To conduct typical engineering hardness tests and be able to recognize commonly used hardness scales and numbers.
- (3) To be able to understand the correlation between hardness numbers and the properties of materials
- (4) To learn the advantages and limitations of the common hardness test methods

Materials: Aluminum welded sample and steel case hardened sample

Instrument: Microhardness tester

For Memo Report:

- (1) Provide table with measured hardness and distance for the 2 microhardness samples
- (2) Graph in Excel, hardness versus distance for the 2 samples to define the case depth.
- (3) Briefly discuss objective topics.

Introduction:

It is a common practice to test materials before they are accepted for processing and put into service to determine whether or not they meet the specifications required. One of these tests is hardness. The Rockwell, Brinell and durometer machines are those most commonly used for this purpose.

1. What is Hardness?

The Metals Handbook defines hardness as "Resistance of metal to plastic deformation, usually by indentation. However, the term may also refer to stiffness or temper, or to resistance to scratching, abrasion, or cutting. It is the property of a metal that gives the ability to resist being permanently deformed (bent, broken, or have its shape changed), when a load is applied. 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. The dictionary of Metallurgy defines the hardness as the resistance of a material to indentation. This is the usual type of hardness test where a pointed or rounded indenter is pressed into a surface under a substantially static load.

2. Hardness Measurements:

Hardness measurement can be defined as macro-, micro- or nano- scale according to the forces applied and displacements obtained [1]. Measurement of macro-hardness is a quick and simple method to obtain mechanical property data for the bulk material from a small sample. It is also widely used for the quality control of surface treatments processes. However, when concerned with coatings and surface properties (important to friction and wear processes), the macro-indentation depth would be too large relative to the surface-scale features.

Where materials have a fine microstructure, are multi-phase, non-homogeneous or prone to cracking, macro-hardness measurements will be highly variable and will not identify individual surface features. It is here that micro-hardness measurements are appropriate. Microhardness is the hardness of a material as determined by forcing an indenter such as a Vickers or Knoop indenter into the surface of the material under 15 to 1000 gf load; usually, the indentations are so small that they must be measured with a microscope. Capable of determining hardness of different microconstituents within a structure, or measuring steep hardness gradients such as those encountered in case hardening. Conversions from microhardness values to tensile strength and other hardness scales (e.g. Rockwell) are available for many metals and alloys [2]. Micro-indenters work by pressing a tip into a sample and continuously measuring: applied load, penetration depth and cycle time.

Nano-indentation tests [3] measure hardness by indenting with a very small, on the order of 1 nano-Newton, indentation force and measuring the depth of the indentation that was made. These tests are based on new technology that allows precise measurement and control of the indenting forces and precise measurement of the indentation depths. By measuring the depth of the indentation, progressive levels of force are measurable on the same piece. This allows the tester to determine the maximum indentation load that is possible before the hardness is compromised and the film is no longer within the testing ranges; providing a check (verification) to be made to determine if the hardness remains constant even after an indentation has been made.

There are various mechanisms and methods that have been designed to complete nano-indentation hardness tests. One method of force application is using a coil and magnet assembly on a loading column to drive the indenter downward. This method uses a capacitance displacement gauge. Such gages detect displacements of 0.2 to 0.3 nm (nanometer) at the time of force application. The loading column is suspended by springs, which damps external motion and allows the load to be released slightly to recover the elastic portion of deformation before measuring the indentation depth. This type of nano-indentation machine can be seen in Figure 1.

Another method of nano-indentation uses a long-range piezo driver and an elastic element as shown in Figure 1b. When the indenter is moved downward by the piezo driver, the elastic element resists the movement and establishes a force. This force is measurable by knowing the distance that the indenter moved downward after touching the film surface. An LVDT (linear variable differential transform) records the position of the shaft, thereby measuring the indentation depth and the spring force applied at one time.

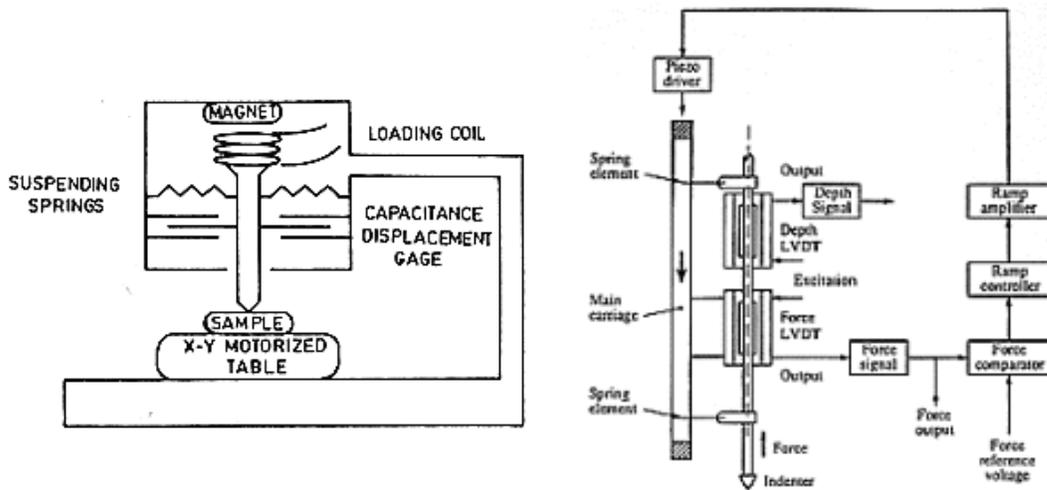


Figure 1a: Nanoindenter that uses a coil and magnet; Figure 1b shows another apparatus that relies on a piezo driver.

3. Hardness Measurement Methods

There are three types of tests used with accuracy by the metals industry; they are the Rockwell hardness test, the Brinell hardness test, and the Vickers hardness test. Since the definitions of metallurgic ultimate strength and hardness are fairly similar, it can generally be assumed that a strong metal is also a hard metal. The way the three of these hardness tests measure a metal's hardness is to determine the metal's resistance to the penetration of a non-deformable ball or cone. The tests determine the depth the ball or cone will sink into the metal, under a given load, within a specific period of time. The following are the most common hardness test methods used in today's technology:

1. Rockwell Hardness test
2. Brinell Hardness
3. Vickers Hardness
4. Knoop Hardness

3.1: Rockwell Hardness Test

The Rockwell Hardness test is a hardness measurement based on the net increase in depth of impression as a load is applied. Hardness numbers have no units and are commonly given in the R, L, M, E and K scales. The higher the number in each of the scales means the harder the material.

Hardness has been variously defined as resistance to local penetration, scratching, machining, wear or abrasion, and yielding. The multiplicity of definitions, and corresponding multiplicity of hardness measuring instruments, together with the lack of a fundamental definition, indicates that hardness may not be a fundamental property of a material, but rather a composite one including yield strength, work hardening, true tensile strength, modulus of elasticity, and others. In the Rockwell method of hardness testing, the depth of penetration of an indenter under certain arbitrary test conditions is

determined. The indenter may either be a steel ball of some specified diameter or a spherical diamond-tipped cone of 120 angle and 0.2 mm tip radius, called Brale. The type of indenter and the test load determine the hardness scale (A, B, C, etc) [4].

A minor load of 10 kg is first applied, which causes an initial penetration and holds the indenter in place. Then, the dial is set to zero and the major load is applied. Upon removal of the major load, the depth reading is taken while the minor load is still on. The hardness number may then be read directly from the scale. The hardness of ceramic substrates can be determined by the Rockwell hardness test, according to the specifications of ASTM E-18. This test measures the difference in depth caused by two different forces, using a dial gauge. Using standard hardness conversion tables, the Rockwell hardness value is determined for the load applied, the diameter of the indenter, and the indentation depth.

The hardness testing of plastics is most commonly measured by the Rockwell hardness test or Shore (Durometer D) hardness test. Both methods measure the resistance of the plastic toward indentation. Both scales provide an empirical hardness value that doesn't correlate to other properties or fundamental characteristics. Rockwell hardness is generally chosen for 'harder' plastics such as nylon, polycarbonate, polystyrene, and acetal where the resiliency or creep of the polymer is less likely to affect the results.

The results obtained from this test are a useful measure of relative resistance to indentation of various grades of plastics. However, the Rockwell hardness test does not serve well as a predictor of other properties such as strength or resistance to scratches, abrasion, or wear, and should not be used alone for product design specifications.

The Rockwell hardness tester to measure the hardness of metal measures resistance to penetration like the Brinell test, but in the Rockwell case, the depth of the impression is measured rather than the diametric area. With the Rockwell tester, the hardness is indicated directly on the scale attached to the machine. This dial like scale is really a depth gauge, graduated in special units. The Rockwell hardness test is the most used and versatile of the hardness tests.

For soft materials such as copper alloys, soft steel, and aluminum alloys a 1/16" diameter steel ball is used with a 100-kilogram load and the hardness is read on the "B" scale. In testing harder materials, hard cast iron and many steel alloys, a 120 degrees diamond cone is used with up to a 150 kilogram load and the hardness is read on the "C" scale. The Rockwell test uses two loads, one applied directly after the other. The first load, known as the "minor", load of 10 kilograms is applied to the specimen to help seat the indenter and remove the effects, in the test, of any surface irregularities.

In essence, the minor load creates a uniformly shaped surface for the major load to be applied to. The difference in the depth of the indentation between the minor and major loads provides the Rockwell hardness number. There are several Rockwell scales other than the "B" & "C" scales, (which are called the common scales). The other scales also use a letter for the scale symbol prefix, and many use a different sized steel ball indenter.

A properly used Rockwell designation will have the hardness number followed by "HR" (Hardness Rockwell), which will be followed by another letter which indicates the specific Rockwell scale. An example is 60 HRB, which indicates that the specimen has a hardness reading of 60 on the B scale. There is a second Rockwell tester referred to as the "Rockwell Superficial Hardness Tester". This machine works the same as the standard Rockwell tester, but is used to test thin strip, or lightly carburized surfaces, small parts or parts that might collapse under the conditions of the regular test. The Superficial tester uses a reduced minor load, just 3 kilograms, and has the major load reduced to either 15 or 45 kilograms depending on the indenter, which are the same ones used for the common scales. Using the 1/16" diameter, steel ball indenter, a "T" is added (meaning thin sheet testing) to the superficial hardness designation. An example of a superficial Rockwell hardness is 15T-22, which indicates the superficial hardness as 22, with a load of 15 kilograms using the steel ball. If the 120 degree diamond cone were used instead, the "T" would be replaced with "N". The ASTM (American Society for Testing & Materials) has standardized a set of scales (ranges) for Rockwell hardness testing. Each scale is designated by a letter.

SCALE: Typical Applications

A Cemented carbides, thin steel and shallow case hardened steel

B Copper alloys, soft steels, aluminum alloys, malleable iron, etc.

C Steel, hard cast irons, pearlitic malleable iron, titanium, deep case hardened steel and other materials harder than B 100

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

H Aluminum, zinc, lead

K, L, M, P, R, S, V Bearing metals and other very soft or thin materials, including plastics.

Standards: ASTM E18 Metals, ISO 6508 Metals, ASTM D785 Plastics

Procedure for Rockwell Test

1. The indenter moves down into position on the part surface
 2. A minor load is applied and a zero reference position is established
 3. The major load is applied for a specified time period (dwell time) beyond zero
 4. The major load is released leaving the minor load applied
- The resulting Rockwell number represents the difference in depth from the zero reference position as a result of the application of the major load (Figure 2).

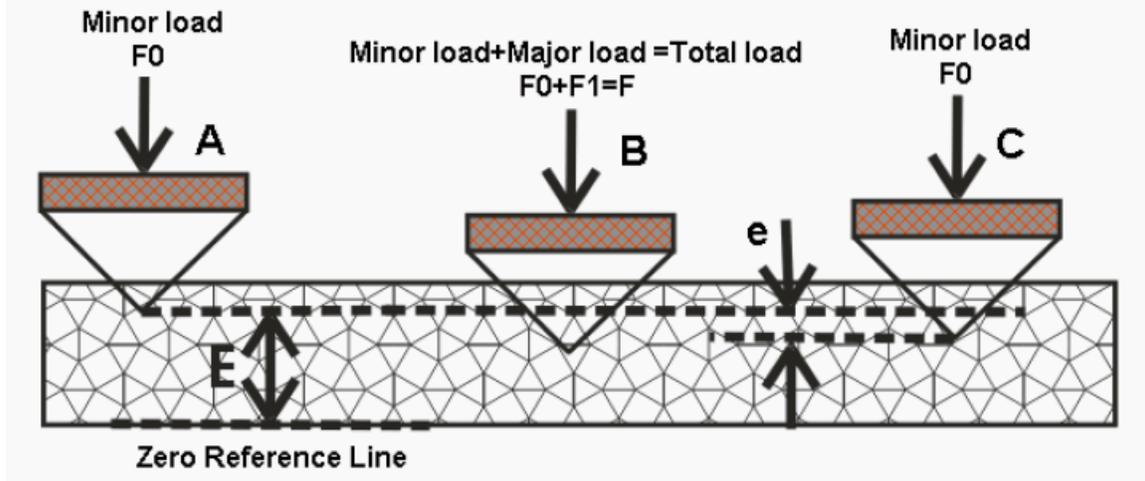


Figure 2: Rockwell hardness testing principle

$$HR = E - e$$

F_0 = preliminary minor load in kgf, F_1 = additional major load in kgf, F = total load in kgf, e = permanent increase in depth of penetration due to major load F_1 measured in units of 0.002 mm, E = a constant depending on form of indenter: 100 units for diamond indenter, 130 units for steel ball indenter, HR = Rockwell hardness number, D = diameter of steel ball.

3.2. Brinell Hardness Test

Brinell hardness is determined by forcing a hard steel or carbide sphere of a specified diameter under a specified load into the surface of a material and measuring the diameter of the indentation left after the test. The Brinell hardness number, or simply the Brinell number, is obtained by dividing the load used, in kilograms, by the actual surface area of the indentation, in square millimeters. The result is a pressure measurement, but the units are rarely stated [5]. **See link on course website for more information.**

Advantages:

1. One scale covers the entire hardness range, although comparable results can only be obtained if the ball size and test force relationship is the same.
2. A wide range of test forces and ball sizes to suit every application.
3. Nondestructive, sample can normally be reused.

Disadvantages:

1. The main drawback of the Brinell test is the need to optically measure the indent size. This requires that the test point be finished well enough to make an accurate measurement.
2. Slow. Testing can take 30 seconds not counting the sample preparation time.

3.3. Vickers Hardness Test

It is the standard method for measuring the hardness of metals, particularly those with extremely hard surfaces: the surface is subjected to a standard pressure for a standard

length of time by means of a pyramid-shaped diamond. The diagonal of the resulting indentation is measured under a microscope and the Vickers Hardness value read from a conversion table [9]. **See link on course website for more information.**

Procedure:

To perform the Vickers test, the specimen is placed on an anvil that has a screw threaded base.

1. The indenter is pressed into the sample by an accurately controlled test force.
2. The force is maintained for a specific dwell time, normally 10 -15 seconds.
3. After the dwell time is complete, the indenter is removed leaving an indent in the sample that appears square shaped on the surface.
4. The size of the indent is determined optically by measuring the two diagonals of the square indent.
5. The Vickers hardness number is a function of the test force divided by the surface area of the indent. The average of the two diagonals is used in the following formula to calculate the Vickers hardness. The operation of applying and removing the load is controlled automatically.

Several loadings give practically identical hardness numbers on uniform material, which is much better than the arbitrary changing of scale with the other hardness machines. A microscope is placed over the specimen to measure the square indentation to a tolerance of plus or minus 1/1000 of a millimeter. Measurements taken across the diagonals to determine the area are averaged. The correct Vickers designation is the number followed "HV" (Hardness Vickers).

Strengths

- 1) One scale covers the entire hardness range.
- 2) A wide range of test forces to suit every application.
- 3) Nondestructive, sample can normally be used.
- 4) The advantages of the Vickers hardness test are that extremely accurate readings can be taken.
- 5) It is very precise for testing the softest and hardest of materials, under varying loads

Weaknesses

- (1) The main drawback of the Vickers test is the need to optically measure the indent size. This requires that the test point be highly finished to be able to see the indent well enough to make an accurate measurement.
- (2) Slow. Testing can take 30 seconds not counting the sample preparation time.
- (3) Vickers machine is a floor standing unit that is rather more expensive than the Brinell or Rockwell machines [11].

4. Relationship of Hardness to Other Material Properties

Hardness covers several properties: resistance to deformation, resistance to friction and abrasion. The well known correlation links hardness with tensile strength (Figure 3), while resistance to deformation is dependent on modulus of elasticity. The frictional resistance may be divided in two equally important parts: the chemical affinity of

materials in contact, and the hardness itself. So it is easy to understand that surface treatments modify frictional coefficients and behavior of the parts in contact. The abrasion resistance is partially related to hardness (between 2 metallic parts in frictional contact, the less hard one will be the more rapidly worn), but experiments show that the correlation resistance against wear/ hardness presents some inversions [28]. A correlation may be established between hardness and some other material property such as tensile strength. Then the other property (such as strength) may be estimated based on hardness test results, which are much simpler to obtain. This correlation depends upon specific test data and cannot be extrapolated to include other materials not tested. The yield strength in tension is about 1/3 of the hardness [29]. To find the ball park figure for the yield strength convert the hardness number to MPa (or psi) and divide by 3. For example take the Vickers number, which has the dimension kg/mm², and multiply by 10 to (approximately) convert it to /mm² (=MPa) then divide by three. For example: HV 300 corresponds to a Sigma-y of approximately 1000 MPa. An approximate relationship between the hardness and the tensile strength (of steel) is,

$$\begin{aligned}
 \text{TS (MPa)} &= \begin{cases} 3.55 \cdot \text{HB} & (\text{HB} \leq 175) \\ 3.38 \cdot \text{HB} & (\text{HB} > 175) \end{cases} \\
 \text{TS (psi)} &= \begin{cases} 515 \cdot \text{HB} & (\text{HB} \leq 175) \\ 490 \cdot \text{HB} & (\text{HB} > 175) \end{cases}
 \end{aligned}$$

Where HB is the Brinell Hardness of the material, as measured with a standard indenter and a 3000 kgf load.

Wear is generally affected by several factors, among them materials selection, friction, surface load, sliding distance, surface hardness, surface finish, and lubrication. Controlling these factors can contribute to a successful application by helping to prevent wear and premature product failure. Wear can be defined as both material loss and deformation at contact surfaces. Wear results in particle generation and surface degradation Properties are high wear resistance; high strength, hardness and fracture toughness; low porosity; high creep and corrosion resistance; The hardness of a metal limits the ease with which it can be machined, since toughness decreases as hardness increases Toughness is a combination of high strength and medium ductility. It is the ability of a material or metal to resist fracture, plus the ability to resist failure after the damage has begun. A tough metal, such as cold chisel, is one that can withstand considerable stress, slowly or suddenly applied, and which will deform before failure. Toughness is the ability of a material to resist the start of permanent distortion plus the ability to resist shock or absorb energy [31].

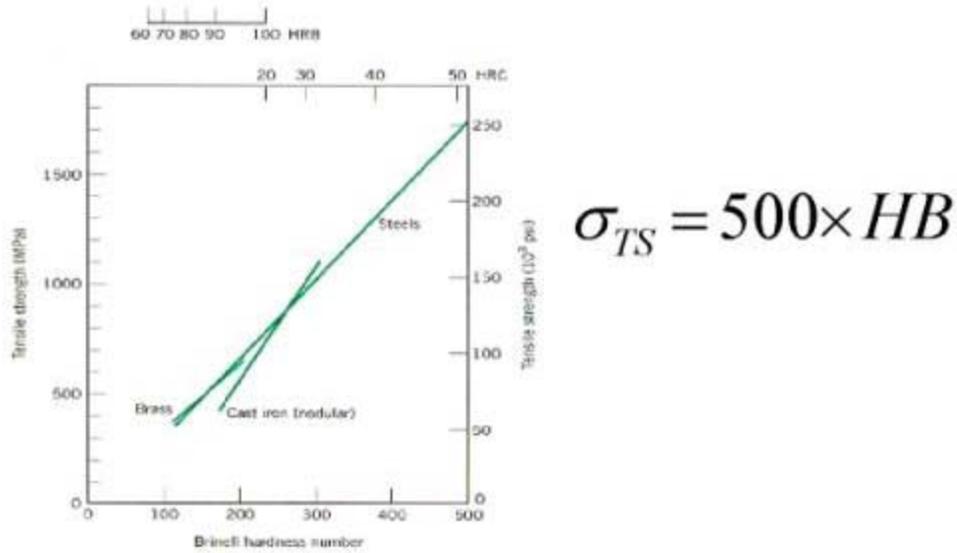


Figure 3: Hardness & Tensile Strength [30]

Additional Tables and References:

TEST	TEST METHOD	TEST FORCE RANGE	INDENTER TYPES	ASTM TEST METHOD	MEASURE METHOD
Rockwell	Regular	60, 100, 150 kgs	Conical Diamond & Small Ball	E 18	Depth
	Superficial	15, 30, 45 kgs	Conical Diamond & Small Ball	E 18	Depth
	Light Load	3, 5, 7 kgs	Truncated Cone Diamond	N/A	Depth
	Micro	500, 100 grams	Small Truncated Cone Diamond	N/A	Depth
	Macro	500 to 3000 kgs	5, 10 mm Ball	E 103	Depth
Micro-Hardness	Vickers	5 to 2000 grams	136° Pyramid Diamond	E 384	Area
	Knoop	5 to 2000 grams	1300 x 1720° Diamond	E 384	Area
	Rockwell Type	500, 3000 grams	Truncated Cone Diamond	N/A	Depth
	Dynamic	.01 to 200 grams	Triangular Diamond	N/A	Depth
Brinell	Optical	500 to 3000 kgs	5mm, 10 mm Ball	E 10	Area
	Depth	500 to 3000 kgs	5mm, 10 mm Ball	E 103	Depth
Shore	Regular	822 (A), 4550 (D) grams	35° Cone (A) 30° Cone (D)	D 2240	Depth
	Micro	257 (A), 1135 (D) grams	35° Cone (A) 30° Cone (D)	N/A	Depth
IRHD	Regular	597 grams	2.5 mm Ball	D 1415	Depth
	Micro	15.7 grams	.395 mm Ball	D 1415	Depth

The summary table for different hardness testing methods [26]

Rockwell C Scale	Brinell Hardness	Vickers Hardness	Tensile Strength (approx.)		Rockwell C Scale	Brinell Hardness	Vickers Hardness	Tensile Strength (approx.)	
Brale Penetrator	10mm Tungsten Carbide Ball	Pyramidic Diamond			Brale Penetrator	10mm Tungsten Carbide Ball	Pyramidic Diamond		
150kgf	3,000kgf	10kgf	ksi	kg/mm ²	150kgf	3,000kgf	10kgf	ksi	kg/mm ²
67	–	900	–	–	43	400	423	201	141
66	–	865	–	–	42	390	412	196	138
65	739	832	–	–	41	381	402	191	134
64	722	800	–	–	40	371	392	186	131
63	705	772	–	–	39	362	382	181	127
62	688	746	–	–	38	353	372	176	124
61	670	720	–	–	37	344	363	172	121
60	654	697	–	–	36	336	354	167	118
59	634	674	329	232	35	327	345	163	114
58	615	653	319	224	34	319	336	159	112
57	595	633	307	216	33	311	327	154	109
56	577	613	297	209	32	301	318	149	105
55	560	595	288	202	31	294	310	146	102
54	543	577	279	196	30	286	302	142	99
53	525	560	269	189	29	279	294	138	97
52	512	544	262	184	28	271	286	134	94
51	496	528	253	178	27	264	279	130	92
50	481	513	245	172	26	258	272	127	89
49	469	498	238	167	25	253	266	125	88
48	455	484	231	162	24	247	260	122	85
47	443	471	224	158	23	243	254	120	84
46	432	458	218	153	22	237	248	116	82
45	421	446	212	149	21	231	243	113	80
44	409	434	206	145	20	226	238	111	78

For the source of Rockwell, Brinell and Vickers Hardness data see endnote 4.

Hardness units conversion table [\[27\]](#)

- [1] <http://www.plint.co.uk/at2/leaflet/te76.htm>
- [2] <http://www.mee-inc.com/microhar.html>
- [3] http://www.ccm.ecn.purdue.edu/tfd/testing_methods/nanoindentation.htm
- [4] http://www.calce.umd.edu/general/Facilities/Hardness_ad_.htm
- [6] <http://www.bikepro.com/products/metals/hardness.html>
- [7] <http://www.wargamer.org/GvA/background/hardness1.html>
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- [11] <http://www.bikepro.com/products/metals/hardness.html>
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- [31] http://www.adtdl.army.mil/cgi-bin/atdl.dll/tc/9-237/Ch7.htm#tab7_1