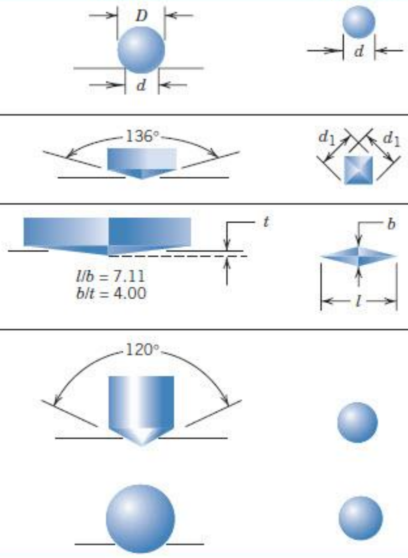
HARDNESS Test

Introduction

Hardness is a characteristic of a solid material expressing its resistance to permanent or plastic deformation. There are three general types of hardness measurements: (1) scratch hardness, (2) Indentation hardness, and (3) rebound or dynamic hardness. Among three only indentation hardness is of major engineering interest for metals. Some of the scales used for indentation hardness in engineering - Rockwell, Vickers, Brinell, and Knoop - can be compared using practical conversion tables for a particular material. The different techniques are shown in Figure 1.

Test	*Indenter*	*Shape of Indentation* — *Side View*	*Shape of Indentation* — *Top View*	*Load*	*Formula for Hardness Number*[a]
Brinell	10-mm sphere of steel or tungsten carbide			P	$HB = \frac{2P}{\pi D[D - \sqrt{D^2 - d^2}]}$
Vickers microhardness	Diamond pyramid			P	$HV = 1.854P/d_1^2$
Knoop microhardness	Diamond pyramid			P	$HK = 14.2P/l^2$
Rockwell and superficial Rockwell	Diamond cone; $\frac{1}{16}$, $\frac{1}{8}$, $\frac{1}{4}$, $\frac{1}{2}$ in.-diameter steel spheres			60 kg, 100 kg, 150 kg } Rockwell; 15 kg, 30 kg, 45 kg } Superficial Rockwell	



[a]For the hardness formulas given, P (the applied load) is in kg, whereas D, d, d_1, and l are all in mm.

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Figure 1. Different hardness test techniques.

When testing metals, indentation hardness correlates linearly with tensile strength. This important relation permits economically important nondestructive testing of bulk materials. There are several mechanisms of hardening of a material system. Some are listed below

1. Strain Hardening (Brass)
2. Precipitation Hardening (Al alloy)
3. Martensitic Transformation (Rapid Quenching) (Steel)
4. Refining Grain Size
5. Solid Solution Strengthening

The indentation techniques involve Brinell, Rockwell, Vickers and Knoop. Different types of indenters are applied for each type. The standard test methods according to the American Society Testing and Materials (ASTM) available are, for instance, **ASTM E10-15a** (Standard test method for Brinell hardness of metallic materials), **ASTM E18-16** (Standard test method for Rockwell hardness of metallic materials), **ASTM E92-16** (Standard test method for Vickers hardness of metallic materials), **ASTM E384-16** (Standard Test Method for Microindentation Hardness of Materials) and **ASTM E140-12b** (Standard Hardness Conversion Tables for Metals Relationship Among Brinell Hardness, Vickers Hardness, Rockwell Hardness, Superficial Hardness, Knoop Hardness, Scleroscope Hardness, and

Leeb Hardness) These hardness testing techniques and conversion tables are selected in relation to specimen dimensions, type of materials and the required hardness information.

Brinell Hardness Test

The Brinell test was devised by a Swedish researcher at the beginning of the 20th century. The test comprises forcing a hardened steel ball indentor into the surface of the sample using a standard load as shown in *Fig.1(a)*. The diameter/load ratio is selected to provide an impression of an acceptable diameter. The ball may be 10, 5 or 1mm in diameter, the load may be 3000, 750 or 30kgf, The load, P, is related to the diameter, D by the relationship P/D^2 and this ratio has been standardised for different metals in order that test results are accurate and reproducible. For steel the ratio is 30:1 - for example a 10mm ball can be used with a 3000kgf load or a 1mm ball with a 30kgf load. For aluminium alloys the ratio is 5:1. The load is applied for a fixed length of time, usually 30 seconds. When the indentor is retracted two diameters of the impression, d_1 and d_2 , are measured using a microscope with a calibrated graticule and then averaged as shown in *Fig.1(b)*.

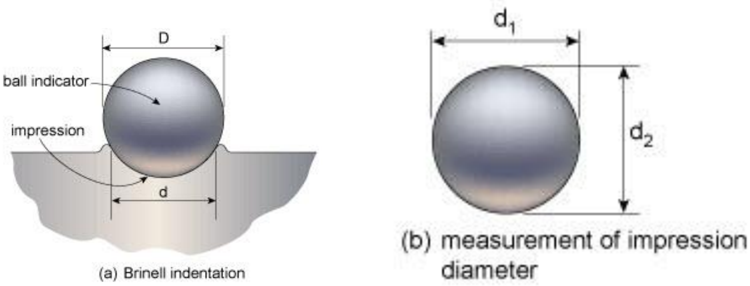

Fig. 1. Brinell Hardness Test (Ref.: http://www.twi-global.com/technical-knowledge/job-knowledge/hardness-testing-part-1-074/)

The *Brinell hardness number* is calculated as:

$$HBW = \frac{2F_{kgf}}{\pi D\left[D - \sqrt{D^2 - d^2}\right]}$$

where:
Fkgf = test force in kgf,
D = diameter of the indenter ball in mm, and
d = measured mean diameter of the indentation in mm

Vickers Hardness Test and Microhardness

The Vickers hardness test operates on similar principles to the Brinell test, the major difference being the use of a square based pyramidal diamond indentor rather than a hardened steel ball. Also, unlike the Brinell test, the depth of the impression does not affect the accuracy of the reading so the P/D^2 ratio is not important. The diamond does not deform at high loads so the results on very hard materials are more reliable. The load may range from 1 to 120kgf and is applied for between 10 and 15 seconds.

As illustrated in *Fig.2(b)* two diagonals, d_1 and d_2 , are measured, averaged and the surface area calculated then divided into the load applied. As with the Brinell test the diagonal measurement is converted to a hardness figure by referring to a set of tables. The hardness may be reported as Vickers Hardness number (VHN), Diamond Pyramid Number (DPN) or, most commonly, Hv_{xx} where 'xx' represents the load used during the test.

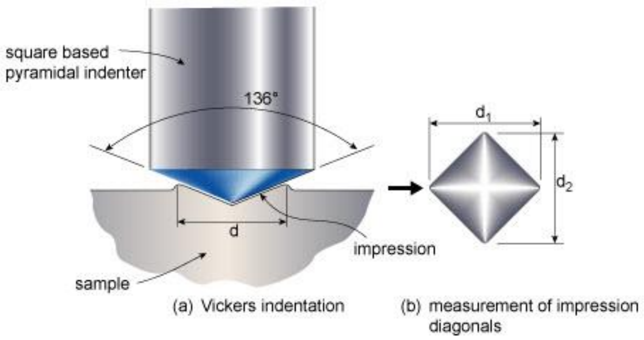

Fig. 2. Vicker hardness test (Ref.: http://www.twi-global.com/technical-knowledge/job-knowledge/hardness-testing-part-1-074/)

Calculation of the Vickers Hardness Number—The Vickers hardness number is based on the indentation test force *F* in kgf divided by the surface area A_S of the indentation in mm².

$$HV = \frac{\text{Test Force}}{\text{Surface Area}} = \frac{F_{(kgf)}}{A_{S\ (mm^2)}}$$

Macroindentation Vickers hardness is typically determined using indentation test forces in kilograms-force (kgf) and indentation diagonals measured in millimetres (mm). The Vickers hardness number, in terms of kgf and mm, is calculated as follows:

$$HV = 1.8544 \text{ x } \frac{F_{(kgf)}}{d_{v\ (mm)}^2}$$

Also, the micro-hardness test has a number of applications varying from being a metallurgical research tool to a method of quality control. The test may be used to determine the hardness of different micro-constituents in a metal, as shown in *Fig.3*. Where an impression would be damaging, for instance on a finished product, micro-hardness tests, particularly the ultrasonic test, may be used for quality control purposes. Micro-hardness testing also finds application in the testing of thin foils, case hardened items and decarburised components.

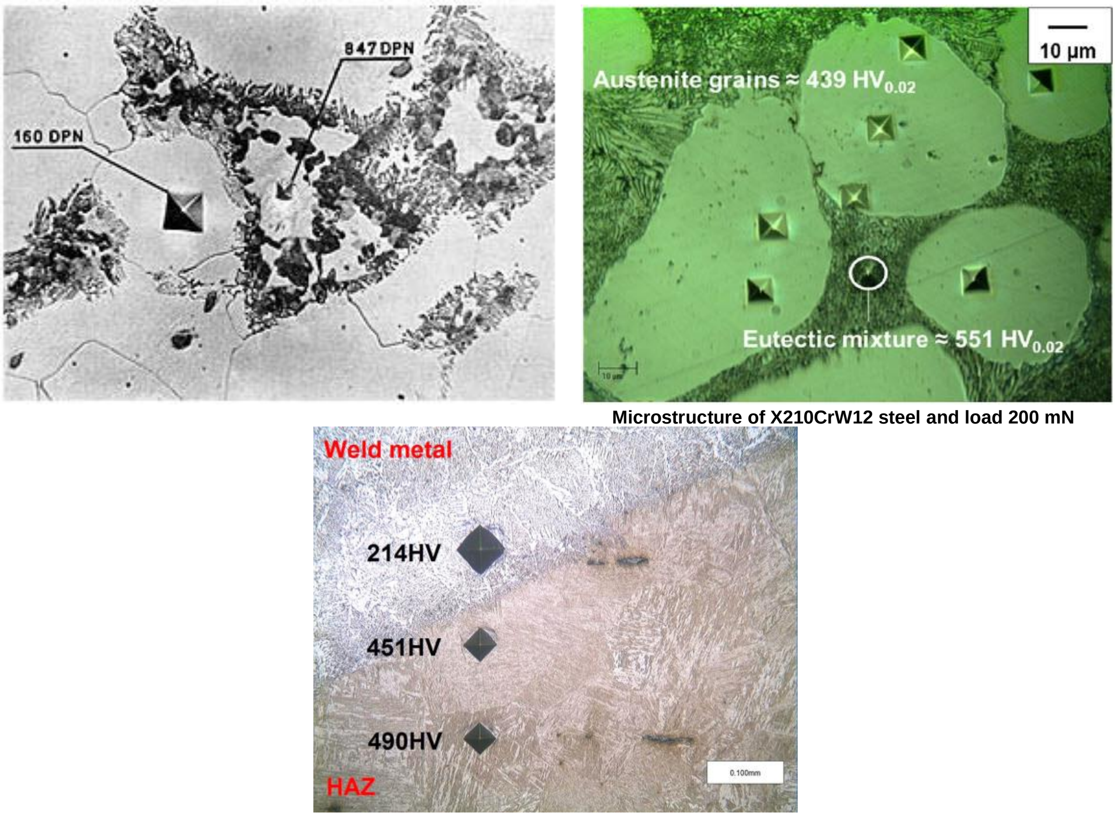

Fig. 3. Microhardness test samples (Ref.: http://metlab.co.nz/microstructures-gallery/ , Researchgate)

Generally more than one indentation is made on a test specimen. It is necessary to ensure that the spacing between indentations is large enough so that adjacent tests do not interfere with each other. For most testing purposes, the minimum recommended spacing between separate tests, and minimum distance between an indentation and the edge of the specimen are illustrated in *Fig. 4*. For some applications, closer spacing of indentations than those shown in *Fig. 4* may be desired. If closer indentation spacing is used, it shall be the responsibility of the testing laboratory to verify the accuracy of the testing procedure.

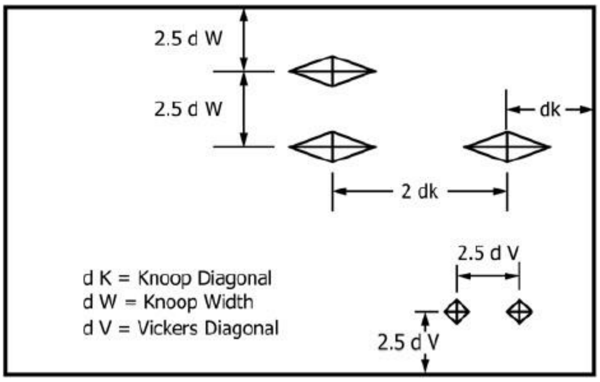

Fig.4. Minimum Recommended Spacing for Vickers and Knoop Indentations

Rockwell Hardness Test

This hardness test uses a direct reading instrument based on the principle of differential depth measurement. Rockwell testing differs from Brinell testing in that the Rockwell hardness number is based on an inverse relationship to the measurement of the additional depth to which an indenter is forced by a heavy (major) load beyond the depth resulting from a previously applied (minor) load. Initially a minor load is applied, and a zero datum position is established. The major load is then applied for a specified period and removed, leaving the minor load applied. The resulting Rockwell number represents the difference in depth from zero datum position as a result of the application of major load. The entire procedure requires only 5 to 10 s.

There are two general classifications of the Rockwell test: the Rockwell hardness test and the Rockwell superficial hardness test. The significant difference between the two test classifications is in the test forces that are used. For the Rockwell hardness test, the preliminary test force is 10 kgf (98 N) and the total test forces are 60 kgf (589 N), 100 kgf (981 N), and 150 kgf (1471 N). For the Rockwell superficial hardness test, the preliminary test force is 3 kgf (29 N) and the total test forces are 15 kgf (147 N), 30 kgf (294 N), and 45 kgf (441 N). Indenters for the Rockwell hardness test include a diamond spheroconical indenter and tungsten carbide ball indenters of specified diameters.

The general principle of the Rockwell indentation hardness test is illustrated in Fig. 5. The test is divided into three steps of force application and removal.

Step 1—The indenter is brought into contact with the testspecimen, and the preliminary test force *F*0 is applied. After holding the preliminary test force for a specified dwell time,the baseline depth of indentation is measured.
Step 2—The force on the indenter is increased at a controlled rate by the additional test force *F*1 to achieve the total test force *F*. The total test force is held for a specified dwell time.
Step 3—The additional test force is removed, returning to the preliminary test force. After holding the preliminary test force for a specified dwell time, the final depth of indentation is measured. The Rockwell hardness value is derived from the difference *h* in the final and baseline indentation depths while under the preliminary test force. The preliminary test force is removed and the indenter is removed from the test specimen.

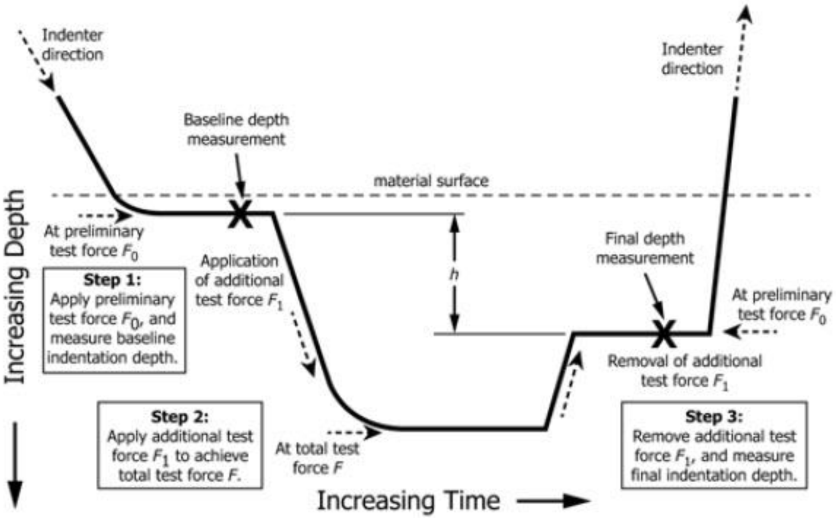

Fig. 5. Rockwell Hardness Test Method (Schematic Diagram)

Calculation of the Rockwell Hardness Number—During a Rockwell test, the force on the indenter is increased from a preliminary test force to a total test force, and then returned to the preliminary test force. The difference in the two indentation depth measurements, while under the preliminary test force, is measured as *h* (see Fig. 5). The unit measurement for *h* is mm. From the value of *h*, the Rockwell hardness number is derived. The Rockwell hardness number is calculated as:

For scales using a diamond spheroconical indenter (see Tables 1 and 2):

$$\text{Rockwell Hardness} = 100 - \frac{\text{h}}{0.002} \qquad \text{Rockwell Superficial Hardness} = 100 - \frac{\text{h}}{0.001}$$

For scales using a ball indenter (see Tables 1 and 2):

$$\text{Rockwell Hardness} = 130 - \frac{\text{h}}{0.002} \qquad \text{Rockwell Superficial Hardness} = 100 - \frac{\text{h}}{0.001}$$

TABLE 1 Rockwell Hardness Scales

Scale Symbol	Indenter	Total Test Force, kgf	Dial Figures	Typical Applications of Scales
B	1⁄16-in. (1.588-mm) ball	100	red	Copper alloys, soft steels, aluminum alloys, malleable iron, etc.
C	diamond	150	black	Steel, hard cast irons, pearlitic malleable iron, titanium, deep case hardened steel, and other materials harder than B100.
A	diamond	60	black	Cemented carbides, thin steel, and shallow case-hardened steel.
D	diamond	100	black	Thin steel and medium case hardened steel, and pearlitic malleable iron.
E	1⁄8-in. (3.175-mm) ball	100	red	Cast iron, aluminum and magnesium alloys, bearing metals.
F	1⁄16-in. (1.588-mm) ball	60	red	Annealed copper alloys, thin soft sheet metals.
G	1⁄16-in. (1.588-mm) ball	150	red	Malleable irons, copper-nickel-zinc and cupro-nickel alloys. Upper limit G92 to avoid possible flattening of ball.
H	1⁄8-in. (3.175-mm) ball	60	red	Aluminum, zinc, lead.
K	1⁄8-in. (3.175-mm) ball	150	red	Bearing metals and other very soft or thin materials. Use smallest ball and heaviest load that does not give anvil effect.
L	1⁄4-in. (6.350-mm) ball	60	red	
M	1⁄4-in. (6.350-mm) ball	100	red	
P	1⁄4-in. (6.350-mm) ball	150	red	
R	1⁄2-in. (12.70-mm) ball	60	red	
S	1⁄2-in. (12.70-mm) ball	100	red	
V	1⁄2-in. (12.70-mm) ball	150	red	

TABLE 2 Rockwell Superficial Hardness Scales

Total Test Force, kgf (N)	Scale Symbols				
	N Scale, Diamond Indenter	T Scale, 1⁄16-in. (1.588-mm) Ball	W Scale, 1⁄8-in. (3.175-mm) Ball	X Scale, 1⁄4-in. (6.350-mm) Ball	Y Scale, 1⁄2-in. (12.70-mm) Ball
15 (147)	15N	15T	15W	15X	15Y
30 (294)	30N	30T	30W	30X	30Y
45 (441)	45N	45T	45W	45X	45Y

References

-- ASM Metals' Handbook
-- ASTM standarts
-- *Materials Science and Engineering*, Eighth Edition, William D. Callister and David G. Rethwisch
-- Web

TASKS

1. Explain the relationship between hardness and tensile strength values.

2. Which metal does provide the highest hardness values? Why?

3. Find Hardness Conversion Tables from the American Society for Mechanical Engineers (ASME) Handbooks web or located in the References Section of the Library. Convert following HRC's to HB and HV values using the tables: 42, 53, 60 (Mark the values also on the table. Attach only the table as an appendix to your lab report!)

4. Discuss the advantages and disadvantages of the Brinell, Vickers and Rockwell Hardness Tests.

Approximate Hardness Conversion Numbers for Non-Austenitic Steels (Rockwell C Hardness Range)[A, B]

Rockwell C Hardness Number 150 kgf (HRC)	Vickers Hardness Number (HV)	Brinell Hardness Number[C] 10-mm Standard Ball, 3000-kgf (HBS)	Brinell Hardness Number[C] 10-mm Carbide Ball, 3000-kgf (HBW)	Knoop Hardness, Number 500-gf and Over (HK)	Rockwell Hardness Number A Scale, 60-kgf (HRA)	Rockwell Hardness Number D Scale, 100-kgf (HRD)	Rockwell Superficial Hardness Number 15-N Scale, 15-kgf (HR 15-N)	Rockwell Superficial Hardness Number 30-N Scale, 30-kgf (HR 30-N)	Rockwell Superficial Hardness Number 45-N Scale, 45-kgf (HR 45-N)	Scleroscope Hardness Number[D]	Rockwell C Hardness Number 150 kgf (HRC)
68	940	...	...	920	85.6	76.9	93.2	84.4	75.4	97.3	68
67	900	...	...	895	85.0	76.1	92.9	83.6	74.2	95.0	67
66	865	...	...	870	84.5	75.4	92.5	82.8	73.3	92.7	66
65	832	...	(739)	846	83.9	74.5	92.2	81.9	72.0	90.6	65
64	800	...	(722)	822	83.4	73.8	91.8	81.1	71.0	88.5	64
63	772	...	(705)	799	82.8	73.0	91.4	80.1	69.9	86.5	63
62	746	...	(688)	776	82.3	72.2	91.1	79.3	68.8	84.5	62
61	720	...	(670)	754	81.8	71.5	90.7	78.4	67.7	82.6	61
60	697	...	(654)	732	81.2	70.7	90.2	77.5	66.6	80.8	60
59	674	...	634	710	80.7	69.9	89.8	76.6	65.5	79.0	59
58	653	...	615	690	80.1	69.2	89.3	75.7	64.3	77.3	58
57	633	...	595	670	79.6	68.5	88.9	74.8	63.2	75.6	57
56	613	...	577	650	79.0	67.7	88.3	73.9	62.0	74.0	56
55	595	...	560	630	78.5	66.9	87.9	73.0	60.9	72.4	55
54	577	...	543	612	78.0	66.1	87.4	72.0	59.8	70.9	54
53	560	...	525	594	77.4	65.4	86.9	71.2	58.6	69.4	53
52	544	(500)	512	576	76.8	64.6	86.4	70.2	57.4	67.9	52
51	528	(487)	496	558	76.3	63.8	85.9	69.4	56.1	66.5	51
50	513	(475)	481	542	75.9	63.1	85.5	68.5	55.0	65.1	50
49	498	(464)	469	526	75.2	62.1	85.0	67.6	53.8	63.7	49
48	484	451	455	510	74.7	61.4	84.5	66.7	52.5	62.4	48
47	471	442	443	495	74.1	60.8	83.9	65.8	51.4	61.1	47
46	458	432	432	480	73.6	60.0	83.5	64.8	50.3	59.8	46
45	446	421	421	466	73.1	59.2	83.0	64.0	49.0	58.5	45
44	434	409	409	452	72.5	58.5	82.5	63.1	47.8	57.3	44
43	423	400	400	438	72.0	57.7	82.0	62.2	46.7	56.1	43
42	412	390	390	426	71.5	56.9	81.5	61.3	45.5	54.9	42
41	402	381	381	414	70.9	56.2	80.9	60.4	44.3	53.7	41
40	392	371	371	402	70.4	55.4	80.4	59.5	43.1	52.6	40
39	382	362	362	391	69.9	54.6	79.9	58.6	41.9	51.5	39
38	372	353	353	380	69.4	53.8	79.4	57.7	40.8	50.4	38
37	363	344	344	370	68.9	53.1	78.8	56.8	39.6	49.3	37
36	354	336	336	360	68.4	52.3	78.3	55.9	38.4	48.2	36
35	345	327	327	351	67.9	51.5	77.7	55.0	37.2	47.1	35
34	336	319	319	342	67.4	50.8	77.2	54.2	36.1	46.1	34
33	327	311	311	334	66.8	50.0	76.6	53.3	34.9	45.1	33
32	318	301	301	326	66.3	49.2	76.1	52.1	33.7	44.1	32
31	310	294	294	318	65.8	48.4	75.6	51.3	32.5	43.1	31
30	302	286	286	311	65.3	47.7	75.0	50.4	31.3	42.2	30
29	294	279	279	304	64.8	47.0	74.5	49.5	30.1	41.3	29
28	286	271	271	297	64.3	46.1	73.9	48.6	28.9	40.4	28
27	279	264	264	290	63.8	45.2	73.3	47.7	27.8	39.5	27
26	272	258	258	284	63.3	44.6	72.8	46.8	26.7	38.7	26
25	266	253	253	278	62.8	43.8	72.2	45.9	25.5	37.8	25
24	260	247	247	272	62.4	43.1	71.6	45.0	24.3	37.0	24
23	254	243	243	266	62.0	42.1	71.0	44.0	23.1	36.3	23
22	248	237	237	261	61.5	41.6	70.5	43.2	22.0	35.5	22
21	243	231	231	256	61.0	40.9	69.9	42.3	20.7	34.8	21
20	238	226	226	251	60.5	40.1	69.4	41.5	19.6	34.2	20

[A] In the table headings, *force* refers to total test forces.

[B] Annex A1 contains equations converting determined hardness scale numbers to Rockwell C hardness numbers for non-austenitic steels. Refer to 1.12 before using conversion equations.

[C] The Brinell hardness numbers in parentheses are outside the range recommended for Brinell hardness testing in 8.1 of Test Method E10.

[D] These Scleroscope hardness conversions are based on Vickers—Scleroscope hardness relationships developed from Vickers hardness data provided by the National Bureau of Standards for 13 steel reference blocks, Scleroscope hardness values obtained on these blocks by the Shore Instrument and Mfg. Co., Inc., the Roll Manufacturers Institute, and members of this institute, and also on hardness conversions previously published by the American Society for Metals and the Roll Manufacturers Institute.

Approximate Hardness Conversion Numbers for Non-Austenitic Steels (Rockwell B Hardness Range)[A, B]

Rockwell B Hardness Number, 100-kgf (HRB)	Vickers Hardness Number (HV)	Brinell Hardness Number, 3000-kgf, (HBS)	Knoop Hardness Number, 500-gf, and Over (HK)	Rockwell A Hardness Number, 60-kgf, (HRA)	Rockwell F Hardness Number, 60-kgf, (HRF)	Rockwell Superficial Hardness Number			Rockwell B Hardness Number, 100-kgf, (HRB)
						15-T Scale, 15-kgf, (HR 15-T)	30-T Scale, 30-kgf, (HR 30-T)	45-T Scale, 45-kgf, (HR 45-T)	
100	240	240	251	61.5	...	93.1	83.1	72.9	100
99	234	234	246	60.9	...	92.8	82.5	71.9	99
98	228	228	241	60.2	...	92.5	81.8	70.9	98
97	222	222	236	59.5	...	92.1	81.1	69.9	97
96	216	216	231	58.9	...	91.8	80.4	68.9	96
95	210	210	226	58.3	...	91.5	79.8	67.9	95
94	205	205	221	57.6	...	91.2	79.1	66.9	94
93	200	200	216	57.0	...	90.8	78.4	65.9	93
92	195	195	211	56.4	...	90.5	77.8	64.8	92
91	190	190	206	55.8	...	90.2	77.1	63.8	91
90	185	185	201	55.2	...	89.9	76.4	62.8	90
89	180	180	196	54.6	...	89.5	75.8	61.8	89
88	176	176	192	54.0	...	89.2	75.1	60.8	88
87	172	172	188	53.4	...	88.9	74.4	59.8	87
86	169	169	184	52.8	...	88.6	73.8	58.8	86
85	165	165	180	52.3	...	88.2	73.1	57.8	85
84	162	162	176	51.7	...	87.9	72.4	56.8	84
83	159	159	173	51.1	...	87.6	71.8	55.8	83
82	156	156	170	50.6	...	87.3	71.1	54.8	82
81	153	153	167	50.0	...	86.9	70.4	53.8	81
80	150	150	164	49.5	...	86.6	69.7	52.8	80
79	147	147	161	48.9	...	86.3	69.1	51.8	79
78	144	144	158	48.4	...	86.0	68.4	50.8	78
77	141	141	155	47.9	...	85.6	67.7	49.8	77
76	139	139	152	47.3	...	85.3	67.1	48.8	76
75	137	137	150	46.8	99.6	85.0	66.4	47.8	75
74	135	135	147	46.3	99.1	84.7	65.7	46.8	74
73	132	132	145	45.8	98.5	84.3	65.1	45.8	73
72	130	130	143	45.3	98.0	84.0	64.4	44.8	72
71	127	127	141	44.8	97.4	83.7	63.7	43.8	71
70	125	125	139	44.3	96.8	83.4	63.1	42.8	70
69	123	123	137	43.8	96.2	83.0	62.4	41.8	69
68	121	121	135	43.3	95.6	82.7	61.7	40.8	68
67	119	119	133	42.8	95.1	82.4	61.0	39.8	67
66	117	117	131	42.3	94.5	82.1	60.4	38.7	66
65	116	116	129	41.8	93.9	81.8	59.7	37.7	65
64	114	114	127	41.4	93.4	81.4	59.0	36.7	64
63	112	112	125	40.9	92.8	81.1	58.4	35.7	63
62	110	110	124	40.4	92.2	80.8	57.7	34.7	62
61	108	108	122	40.0	91.7	80.5	57.0	33.7	61
60	107	107	120	39.5	91.1	80.1	56.4	32.7	60
59	106	106	118	39.0	90.5	79.8	55.7	31.7	59
58	104	104	117	38.6	90.0	79.5	55.0	30.7	58
57	103	103	115	38.1	89.4	79.2	54.4	29.7	57
56	101	101	114	37.7	88.8	78.8	53.7	28.7	56
55	100	100	112	37.2	88.2	78.5	53.0	27.7	55
54	...	...	11	36.8	87.7	78.2	52.4	26.7	54
53	...	...	110	36.3	87.1	77.9	51.7	25.7	53
52	...	...	109	35.9	86.5	77.5	51.0	24.7	52
51	...	...	108	35.5	86.0	77.2	50.3	23.7	51
50	...	...	107	35.0	85.4	76.9	49.7	22.7	50
49	...	...	106	34.6	84.8	76.6	49.0	21.7	49
48	...	...	105	34.1	84.3	76.2	48.3	20.7	48
47	...	...	104	33.7	83.7	75.9	47.7	19.7	47
46	...	...	103	33.3	83.1	75.6	47.0	18.7	46
45	...	...	102	32.9	82.6	75.3	46.3	17.7	45
44	...	...	101	32.4	82.0	74.9	45.7	16.7	44
43	...	...	100	32.0	81.4	74.6	45.0	15.7	43
42	...	...	99	31.6	80.8	74.3	44.3	14.7	42
41	...	...	98	31.2	80.3	74.0	43.7	13.6	41
40	...	...	97	30.7	79.7	73.6	43.0	12.6	40
39	...	...	96	30.3	79.1	73.3	42.3	11.6	39
38	...	...	95	29.9	78.6	73.0	41.6	10.6	38
37	...	...	94	29.5	78.0	72.7	41.0	9.6	37
36	...	...	93	29.1	77.4	72.3	40.3	8.6	36
35	...	...	92	28.7	76.9	72.0	39.6	7.6	35
34	...	...	91	28.2	76.3	71.7	39.0	6.6	34
33	...	...	90	27.8	75.7	71.4	38.3	5.6	33
32	...	...	89	27.4	75.2	71.0	37.6	4.6	32
31	...	...	88	27.0	74.6	70.7	37.0	3.6	31
30	...	...	87	26.6	74.0	70.4	36.3	2.6	30

[A] In table headings, kgf refers to total test force.
[B] Annex A2 contains equations converting determined hardness numbers to Rockwell B hardness numbers for non-austenitic steels. Refer to 1.12 before using conversion equations.