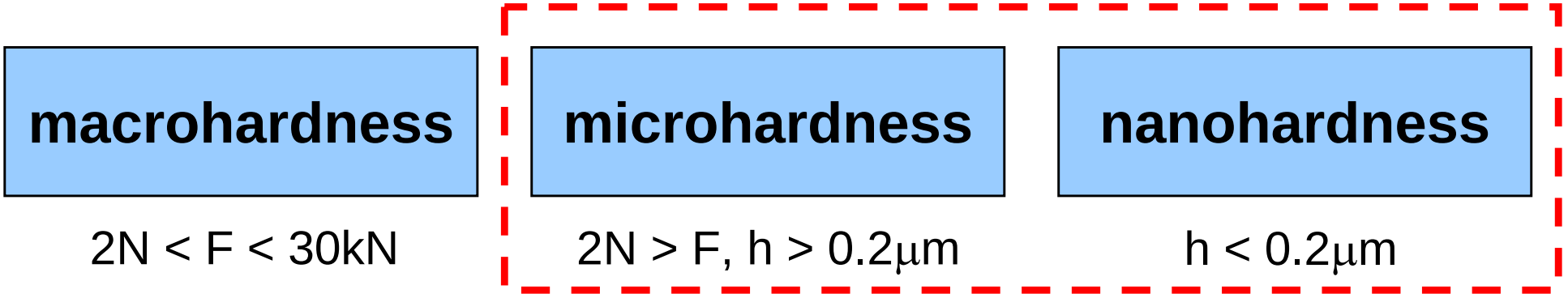
Hardness Tests [3]

➢ **HARDNESS**: **the resistance of a material to deformation, particularly permanent deformation, indentation, or scratching**.

➢ **DISCUSSION**: Different methods of evaluating hardness give different ratings because they are measuring somewhat different quantities and characteristics of the material. There is no absolute scale for hardness; therefore, to express hardness quantitatively, each type of test has its own scale of arbitrarily defined hardness.

(after ASTM E6).

➢ **Ranges of application:**



F – force
h – depth

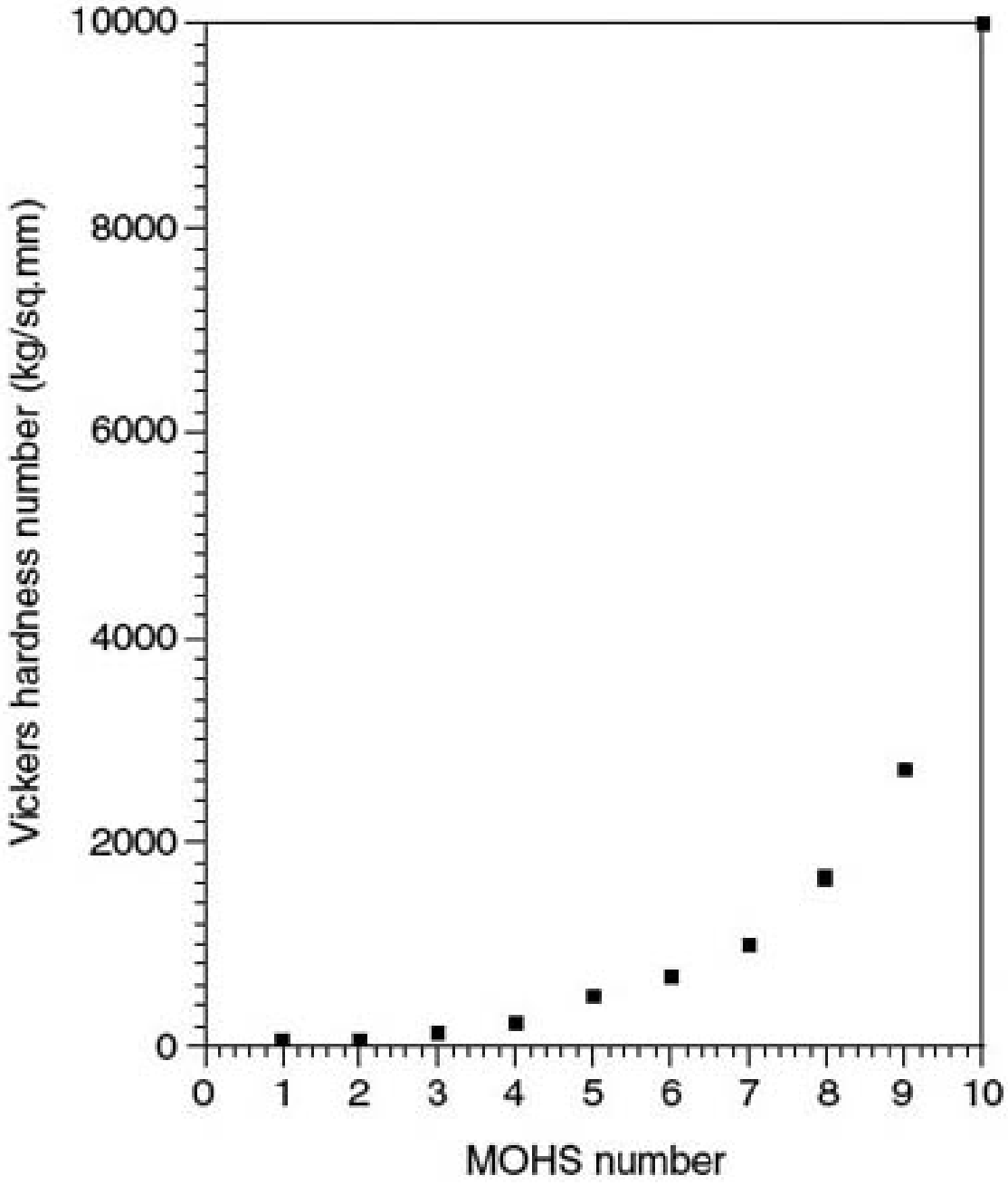
Mohs Hardness Test

The **Mohs scale of mineral hardness** is a qualitative ordinal scale that characterizes the scratch resistance of various minerals through the ability of a harder material to scratch a softer material. It was created in 1812 by the German geologist and mineralogist **Friedrich Mohs** (1773-1839).

	Mineral	Chemical formula	Image
1	Talc	$Mg_3Si_4O_{10}(OH)_2$	
2	Gypsum	$CaSO_4 \cdot 2H_2O$	
3	Calcite	$CaCO_3$	
4	Fluorite	CaF_2	
5	Apatite	$Ca_5(PO_4)_3(OH^-,Cl^-,F^-)$	
6	Orthoclase feldspar	$KAlSi_3O_8$	
7	Quartz	SiO_2	
8	Topaz	$Al_2SiO_4(OH^-,F^-)$	
9	Corundum	Al_2O_3	
10	Diamond	C	

after Wikipedia (2016)

Mohs Hardness Test



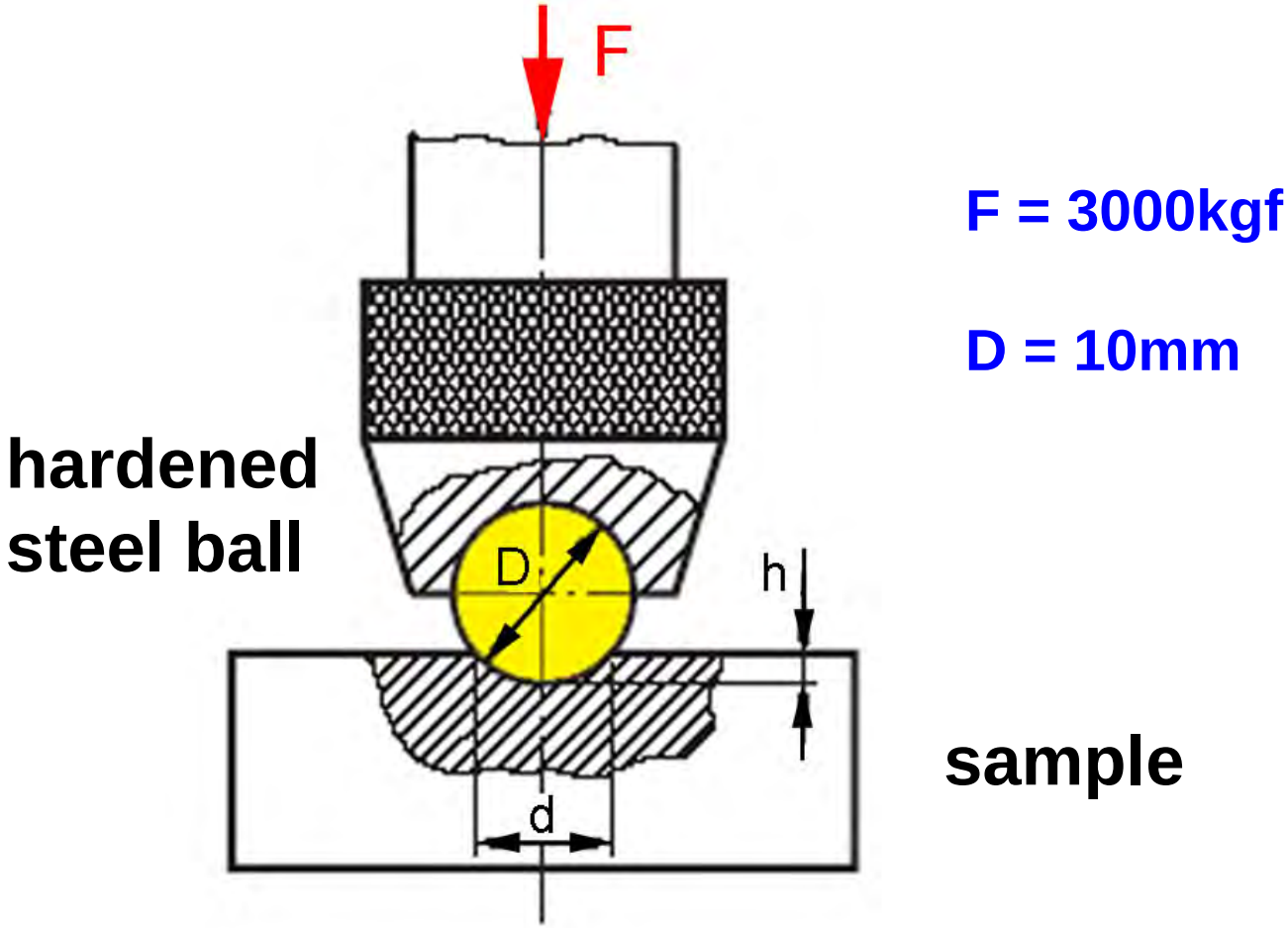
MOHS #	Crystal
1	Talc
2	Gypsum
3	Calcite
4	Fluorite
5	Apatite
6	Orthoclase
7	Quartz
8	Topaz
9	Sapphire
10	Diamond

after Gilman (2009)

Brinell Hardness Test

➢ The **Brinell Hardness** characterizes the indentation hardness of materials through the scale of penetration of an indenter, loaded on a material test-piece. It is one of several definitions of hardness in materials science. Proposed by Swedish engineer **Johan August Brinell** (1849-1925) in 1900, it was the first widely used and standardized hardness test in engineering and metallurgy.

J. A. Brinell



hardened steel ball

F = 3000kgf

D = 10mm

sample

Brinell Hardness Test

- **Brinell/Vickers durometer:**
- Selectable load
  from 1 to 187,5kgf
- hard metal / steel balls
  1; 2.5; 5 and 10mm diameter
- optical micrometer
- procedure: ASTM E10

Brinell Hardness Test

- **Calculation of Brinell Hardness HBW:**

$$HBW = \frac{2 \cdot F}{\pi \cdot D \cdot (D - \sqrt{D^2 - d^2})}$$

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

- **The Brinell hardness test is not recommended for materials above 650 HBW.**
- **Applied force dwell time: 10 to 15 seconds.**

after ASTM E10 (2015)

Brinell Hardness Test

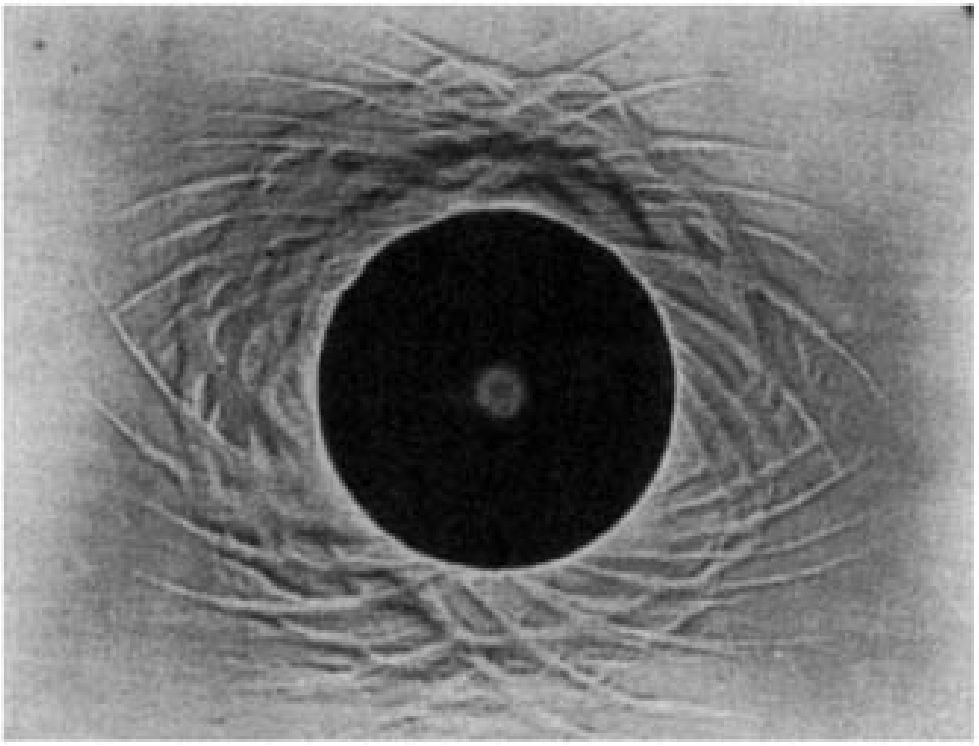
- **Applied force according to ASTM E10:**

	Force-Diameter ratio (F/D^2)				
D [mm]	30	10	5	2,5	1
10	3000	1000	500	250	100
5	750	250	125	62,5	25
2.5	187.5	62.5	31.25	15.625	6.25
1	30	10	5	2,5	1
	A	B	C	D	E

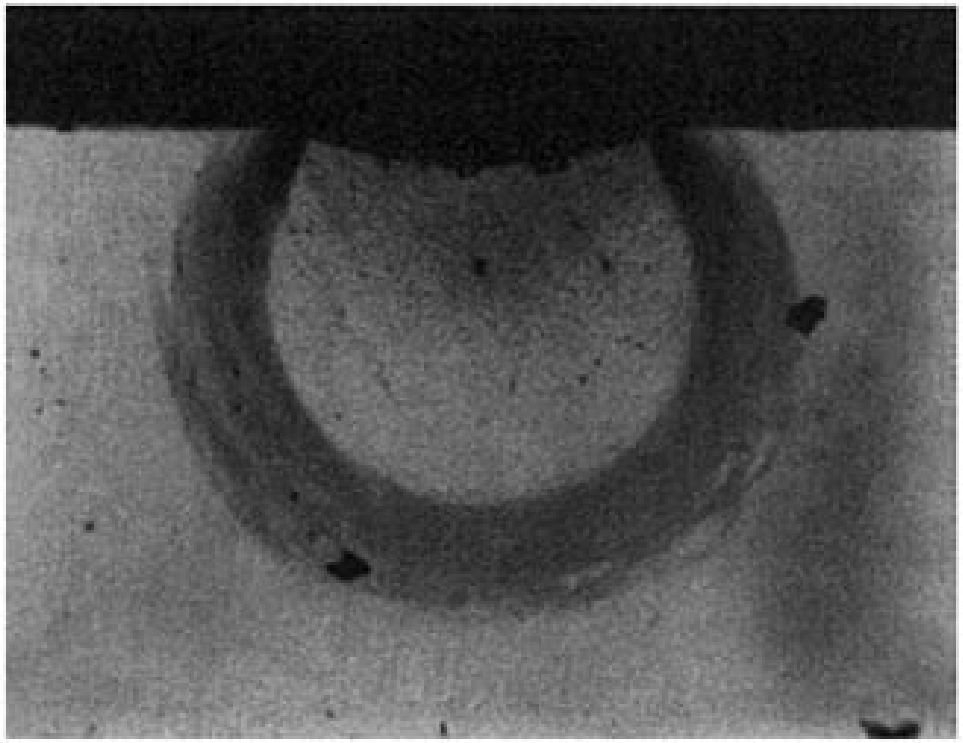
A: steels and iron alloys;
B: heat treated Cu/Al light alloys;
C: no heat treated Cu/Al light alloys;
D-E: soft metallic materials.

Brinell Hardness Test

- **Deformed zone near Brinell indentation:**



Top view



Transverse view

- Indentation size: 0.24 D < d < 0.6 D
- Sample thickness > 10 times the depth of penetration, h.
- Minimum distance between indentations must be 3 times d.

after Herrman (2011)

Brinell Hardness Test

- **Expressing results according to ASTM E10:**

220 HBW

- **Brinell hardness of 220 determined with a ball of 10 mm diameter and with a test force of 29.42 kN (3000 kgf) applied for 10 s to 15 s;**

350 HBW 5/750

- **Brinell hardness of 350 determined with a ball of 5 mm diameter and with a test force of 7.355 kN (750 kgf) applied for 10 s to 15 s;**

600 HBW 1/30/20

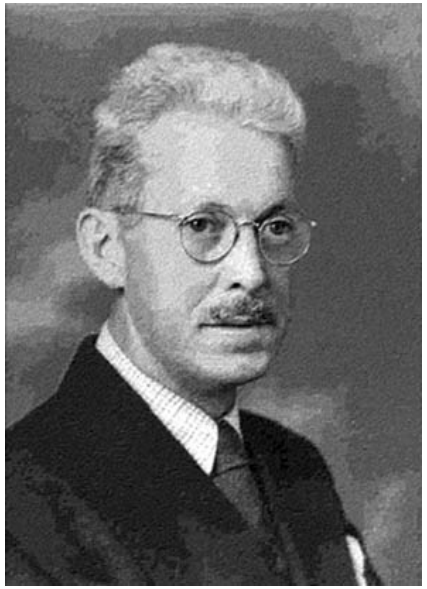
- **Brinell hardness of 600 determined with a ball of 1 mm diameter and with a test force of 294.2 N (30 kgf) applied for 20 s;**

after ASTM E10 (2015)

Rockwell Hardness Test

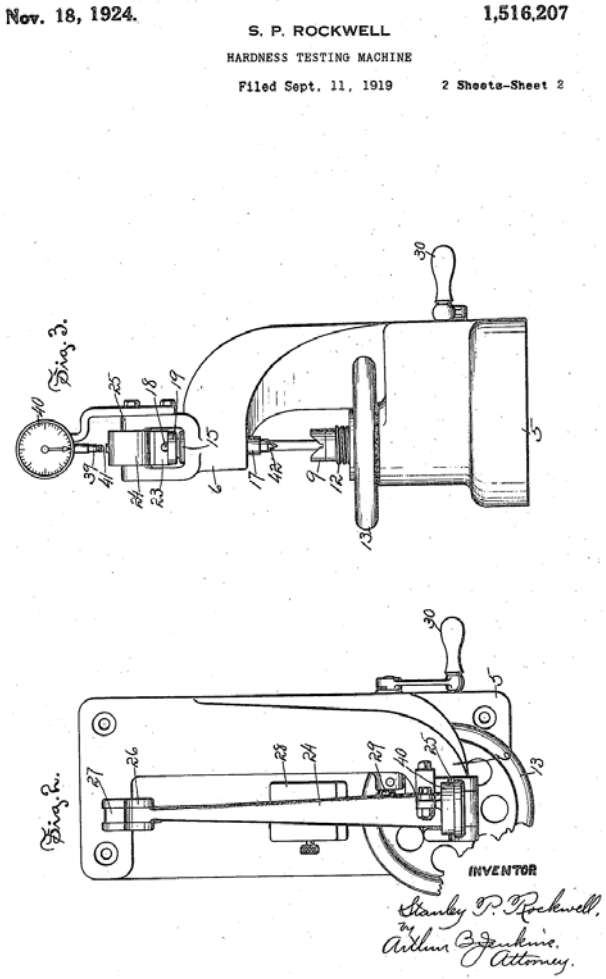
➢ **Hugh M. Rockwell** (1890–1957) and **Stanley P. Rockwell** (1886–1940) co-Invented in 1914 the "Rockwell hardness tester", a differential-depth machine. Stanley contributed to develop and commercialize in 1924 his standardized testing machines manufactured by Wilson Mechanical Instrument Company.

H. M. Rockwell



S. P. Rockwell

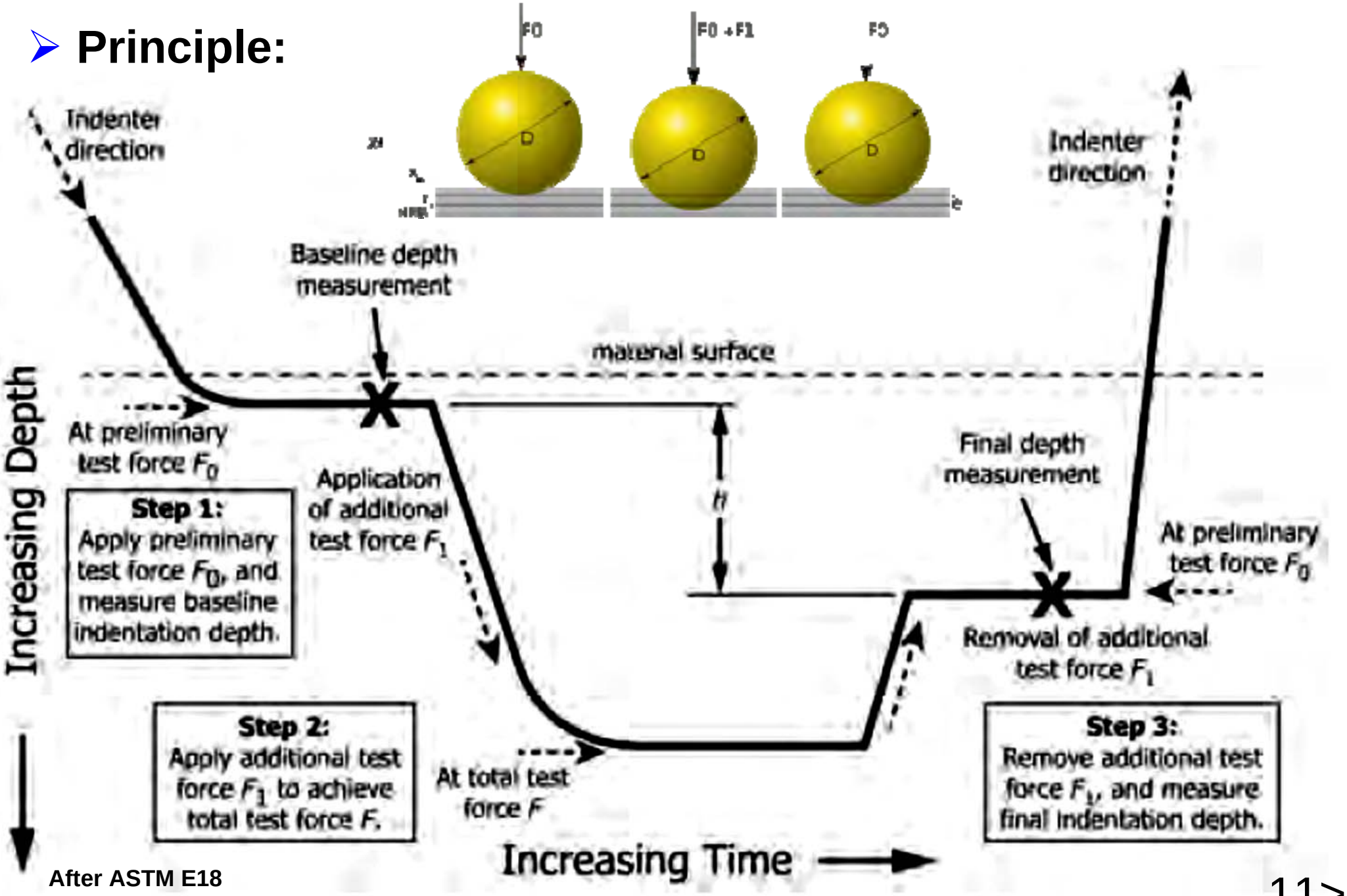
Hardness-testing machine
Patent US 1516207 A
(1924)



after Wikipedia (2016)

Rockwell Hardness Test

- **Principle:**



After ASTM E18

Rockwell Hardness Test

- **Types of indenters:**

Hard metal ball indenters
1/16”; 1/8”; 1/4” and 1/2”

diamond spheroconical indenter
120°; 0.2mm radius of curvature
(Brale indenter)

After ASTM E18

Rockwell Hardness Test

➢ 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	

➢ Brale indenter → $\text{Rockwell Hardness} = 100 - \frac{h}{0.002}$

➢ Ball indenter → $\text{Rockwell Hardness} = 130 - \frac{h}{0.002}$

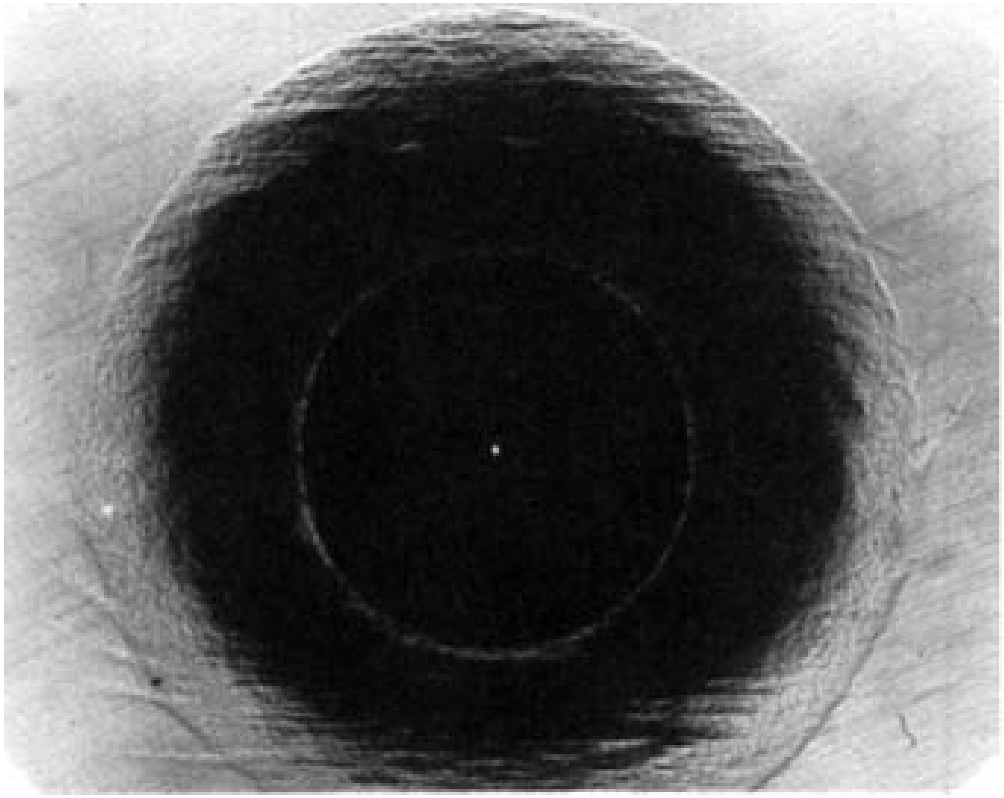
After ASTM E18

➢ **Dwell time: 5-10 seconds**

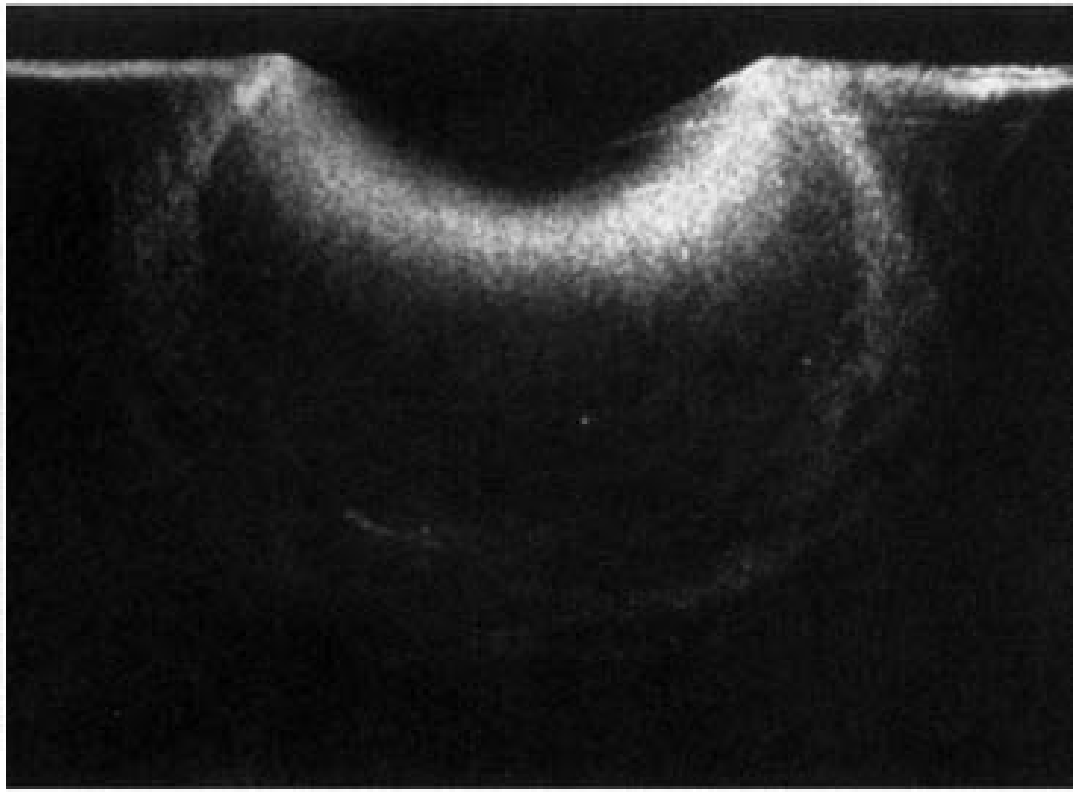
Rockwell Hardness Testing Machine

Rockwell Hardness Test

- **Deformed zone near Rockwell indentation (HRC):**



Top view



Transverse view

- Sample thickness > 10 times the depth of penetration, h.
- Minimum distance between indentations must be 3 times d.

after Herrman (2011)

Rockwell Hardness Test

- **Expressing results according to ASTM E18:**

64 HRC

- **Rockwell hardness number of 64 on Rockwell C scale using a Brale indenter with a total force test of 150 kgf.**

72 HRBW

- **Rockwell hardness number of 72 on the Rockwell B scale using a 1/16” tungsten carbide ball indenter (1.588-mm) with a total force test of 100 kgf.**

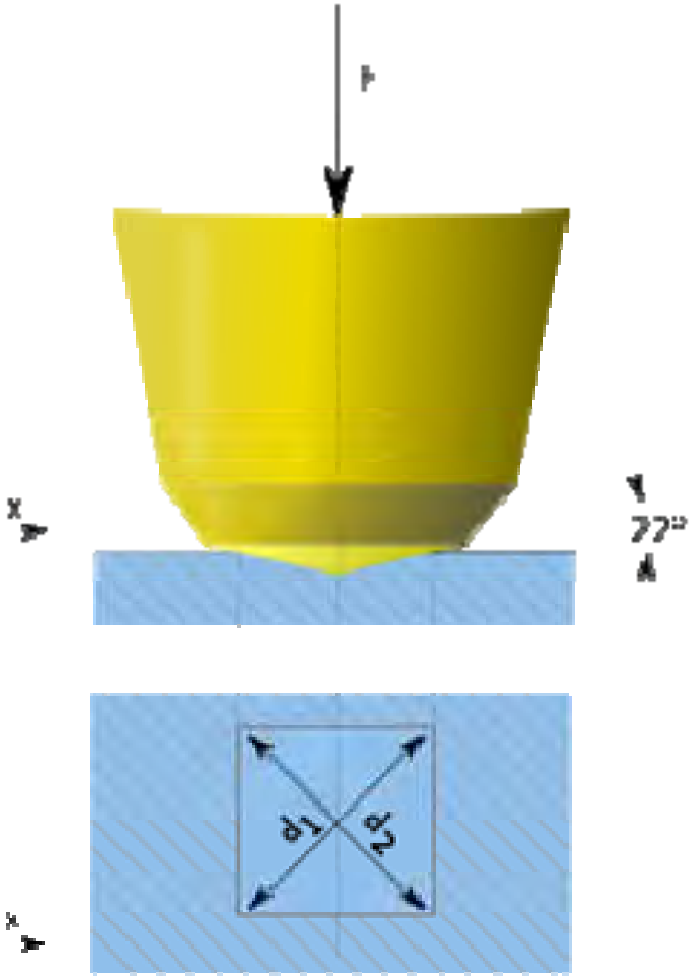
53 HRFS

- **Rockwell hardness number of 53 on the Rockwell F scale using a 1/16” hardened steel ball indenter (1.588-mm) with a total force test of 60 kgf.**

after ASTM E18 (2015)

Vickers Hardness Test

➢ The **Vickers hardness test** was developed in 1921 by Robert L. Smith and George E. Sandland at Vickers Ltd as an alternative to the Brinell method to measure the hardness of materials. The Vickers test has a great advantage of using one hardness scale to test all materials.



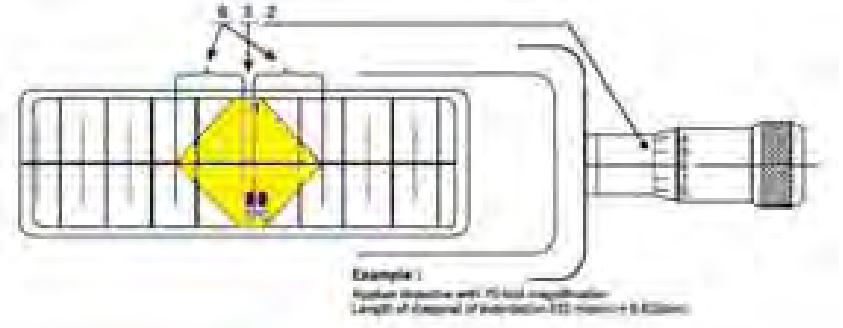
after Wikipedia (2016)

Vickers Hardness Test

- **Brinell/Vickers durometer:**
- Selectable load

  from 1 to 187,5kgf
- pyramidal indenter

- optical micrometer

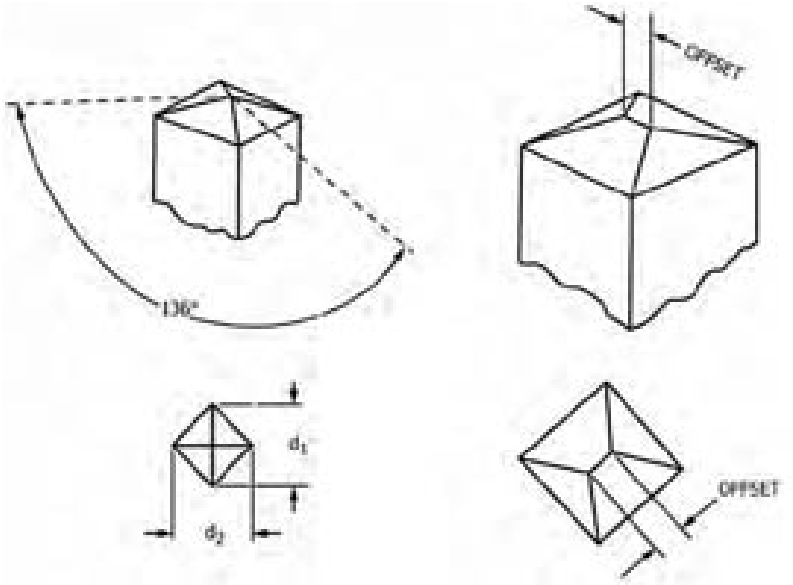


- procedure: ASTM E384

Vickers Hardness Test

- **Calculation of Vickers Hardness HV:**

$$HV = 1.8544 \cdot \frac{F}{d^2}$$



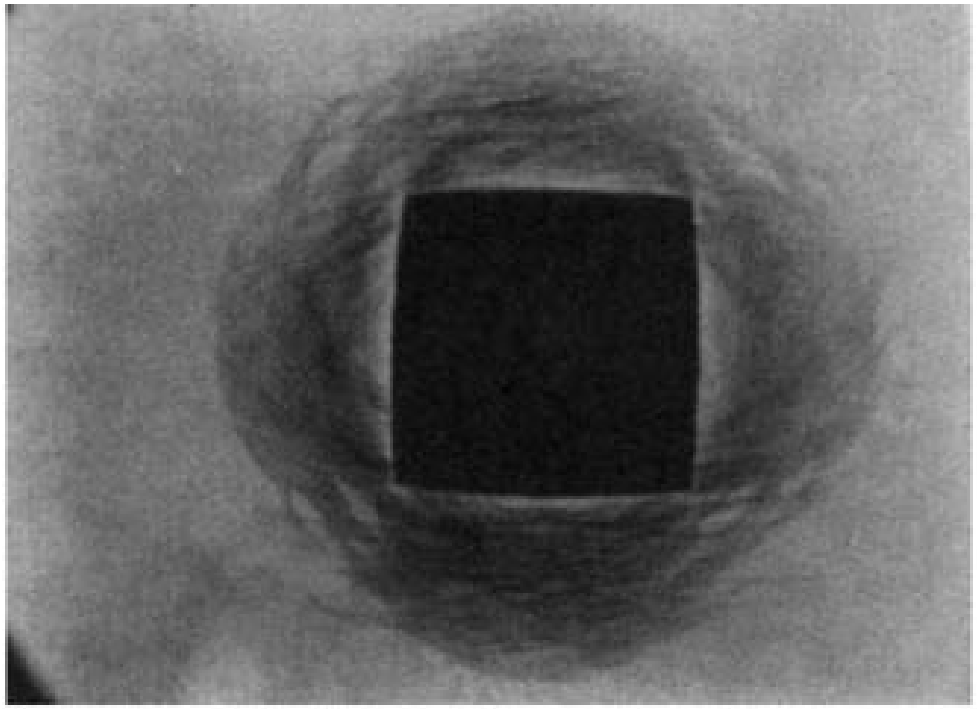
where:
F = test force in kgf,
d = measured mean diagonal of the indentation in mm.

- **Vickers hardness testing is divided into 2 ranges:**
  - **microhardness: 1≤ F ≤ 1000 gf**
  - **macrohardness: 1≤ F ≤ 120 kgf**
- **Applied force dwell time: 10 to 15 seconds.**

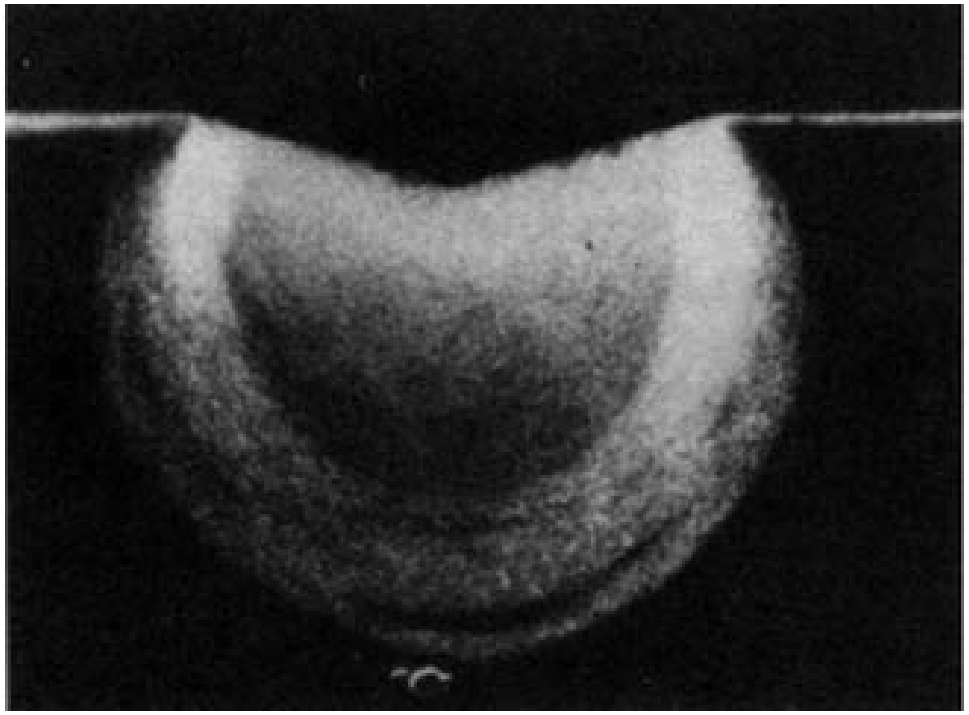
after ASTM E384 (2011)

Vickers Hardness Test

- **Deformed zone near Vickers indentation:**



Top view



Transverse view

- Sample thickness > 10 times the depth of penetration, h.
- Minimum distance between indentations must be 3 times d.

after Herrman (2011)

Vickers Hardness Test

- **Expressing HV results according to ASTM E384:**

250 HV 1

- **Vickers hardness number of 250 kgf/mm^2 using a force test of 1 kgf during 10 to 15 seconds.**

510 HV 10/30

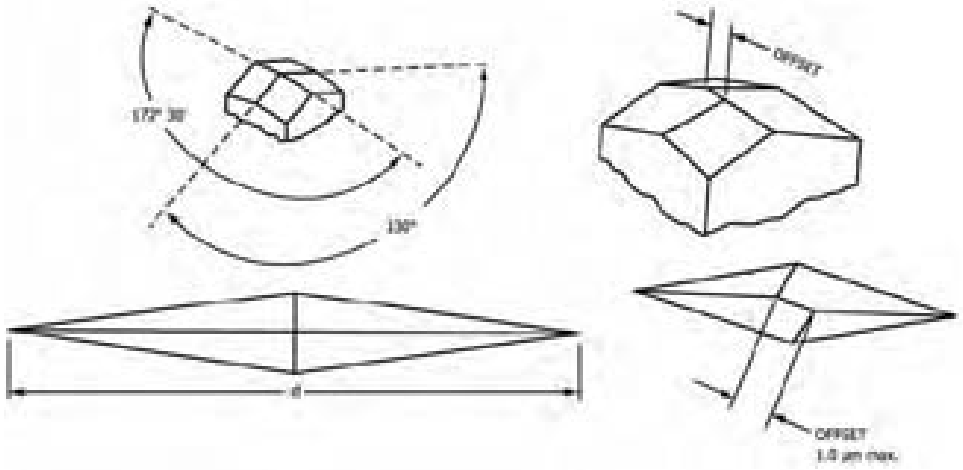
- **Vickers hardness number of 510 kgf/mm^2 using a force test of 10 kgf during 30 seconds.**

after ASTM E384 (2011)

Knoop Hardness Test

- **The test was developed by Frederick Knoop and colleagues at the National Bureau of Standards (now NIST) of the USA in 1939.**
- **Calculation of Knoop Hardness HK:**

$$HK = 14.229 \cdot \frac{F}{d^2}$$



where:
F = test force in kgf,
d = length of long diagonal of the indentation in mm.

- **Knoop hardness testing is usually applied in micro-hardness range: 1≤ F ≤ 1000 gf**

- **Applied force dwell time: 10 to 15 seconds.**

after ASTM E384 (2011)

Knoop Hardness Test

- **Expressing HK results according to ASTM E384:**

250 HK 0.1

- **Knoop hardness number of 250 kgf/mm^2 using a force test of 0.1 kgf (100 gf) during 10 to 15 seconds.**

510 HK 0.5/30

- **Knoop hardness number of 510 kgf/mm^2 using a force test of 0.5 kgf (500 gf) during 30 seconds.**

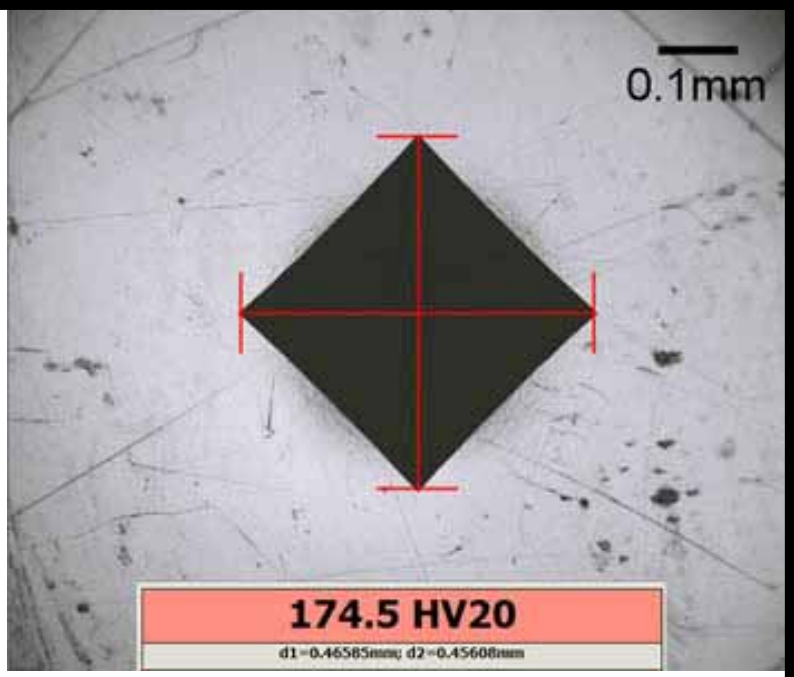
after ASTM E384 (2011)

Examples of Indentation

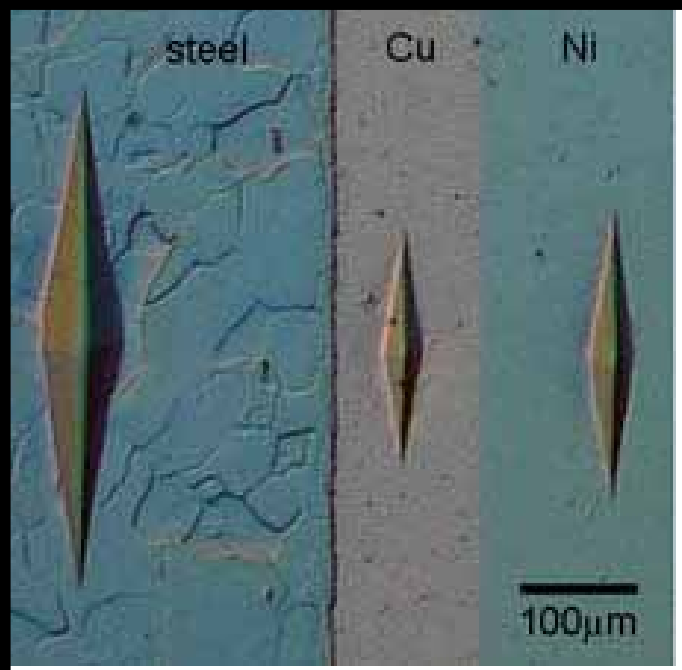
HBW

HRC

HV



HK



Standard Hardness Conversion Tables for Metals

➢ ASTM E140: Approximate hardness conversion

TABLE 1 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]		Knoop Hardness, Number 500-gf and Over (HK)	Rockwell Hardness Number		Rockwell Superficial Hardness Number			Sclero-scope Hardness Number[D]	Rockwell C Hardness Number 150 kgf (HRC)
		10-mm Standard Ball, 3000-kgf (HBS)	10-mm Carbide Ball, 3000-kgf (HBW)		A Scale, 60-kgf (HRA)	D Scale, 100-kgf (HRD)	15-N Scale, 15-kgf (HR 15-N)	30-N Scale, 30-kgf (HR 30-N)	45-N Scale, 45-kgf (HR 45-N)		
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

after ASTM E140 (2012)

Standard Hardness Conversion Tables for Metals

➢ ASTM E140: Approximate hardness conversion

TABLE 2 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

after ASTM E140 (2012)

Standard Hardness Conversion Tables for Metals

➢ ASTM E140: HARDNESS CONVERSION EQUATIONS FOR NON-AUSTENITIC STEELS

A1.1.1 From Vickers hardness to Rockwell C hardness:

$$HRC = +3.14900E+01 + 7.96683E\text{-}02(HV) - 3.55432E\text{-}05(HV)^2 - 6.72816E+03(HV)^{-1} \quad (A1.1)$$

A1.1.2 From Brinell hardness (10-mm diameter steel ball, 3000-kgf force) to Rockwell C hardness:

$$HRC = +8.35260E+01 - 8.68203E\text{-}02(HBS) + 1.44229E\text{-}04(HBS)^2 - 1.15905E+04(HBS)^{-1} \quad (A1.2)$$

A2.1.1 From Vickers hardness to Rockwell B hardness:

$$HRB = +1.14665E+02 + 8.82795E\text{-}02(HV) - 1.41855E\text{-}04(HV)^2 - 6.69528E+03(HV)^{-1} \quad (A2.1)$$

A2.1.2 From Brinell hardness (10-mm diameter steel ball, 3000-kgf force) to Rockwell B hardness:

$$HRB = +1.14665E+02 + 8.82795E\text{-}02(HBS) - 1.41855E\text{-}04(HBS)^2 - 6.69528E+03(HBS)^{-1} \quad (A2.2)$$

- **there are similar equations for austenitic steels, Ni alloys, Cu alloys, and Al alloys.**

after ASTM E140 (2012)

References

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