Mechanical Behaviour of Materials

Chapter 3

Mechanical testing: Hardness

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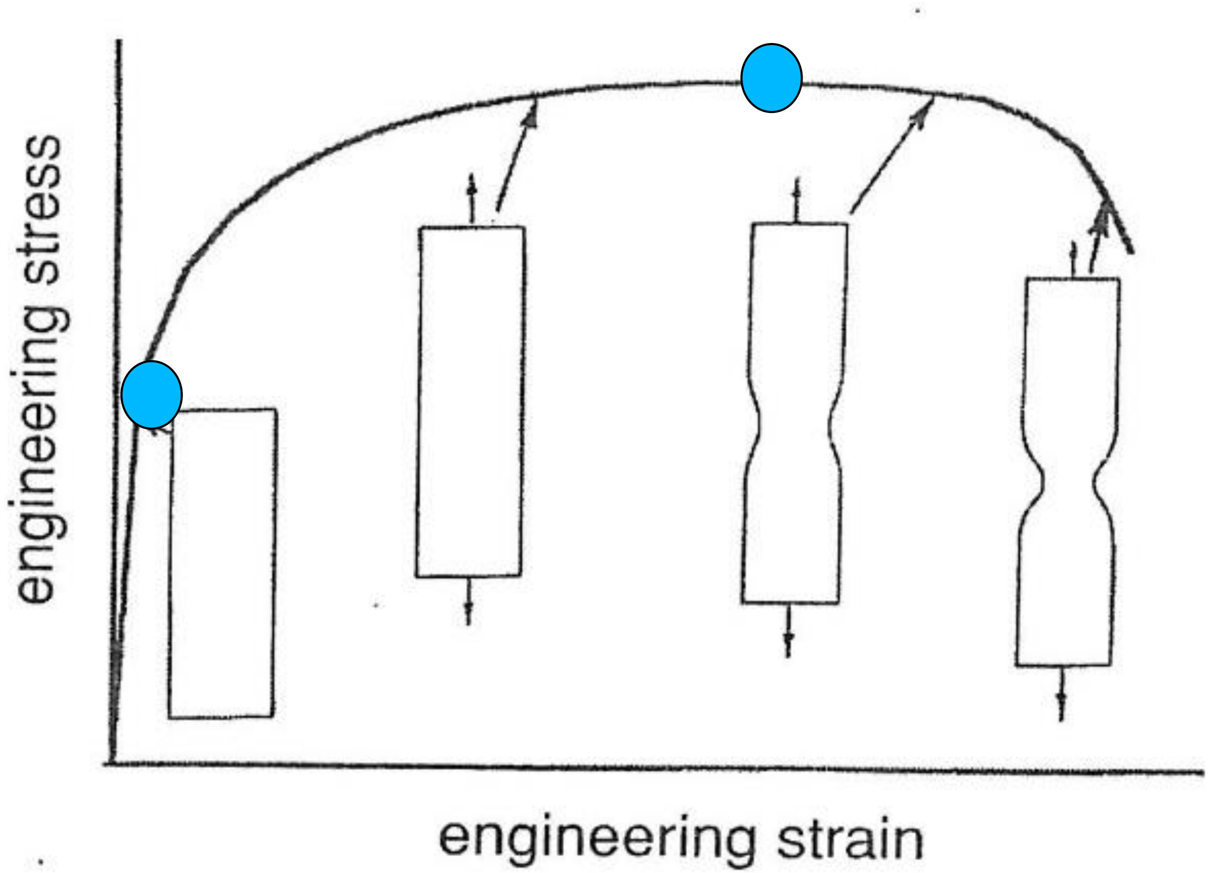
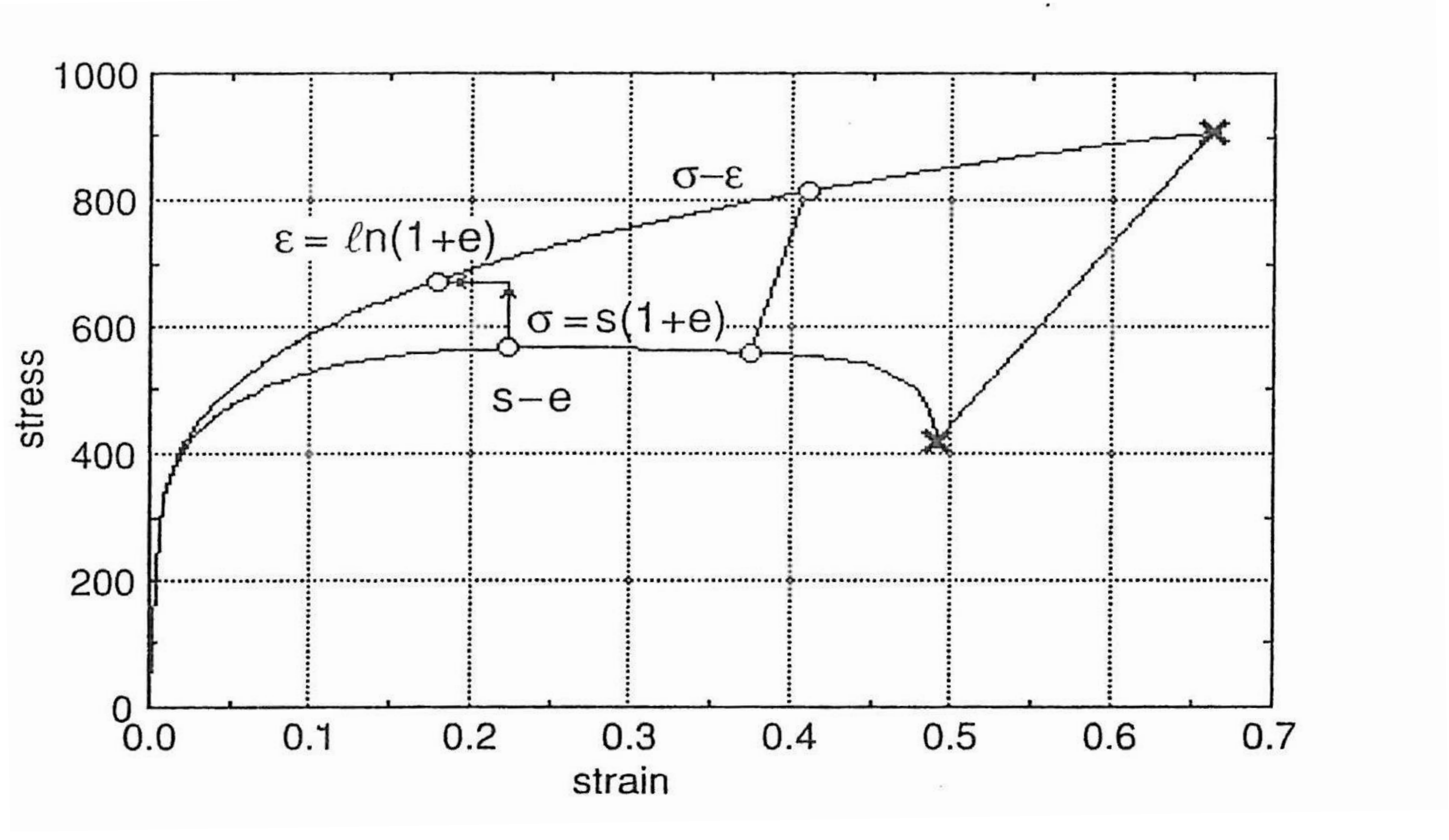
Stress-strain curve



True stress and strain

$$\sigma_t = \sigma(1+\varepsilon) \qquad \varepsilon_t = \ln(1+\varepsilon)$$



Compression test

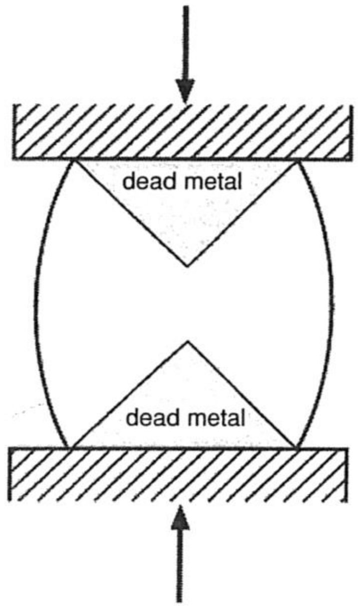
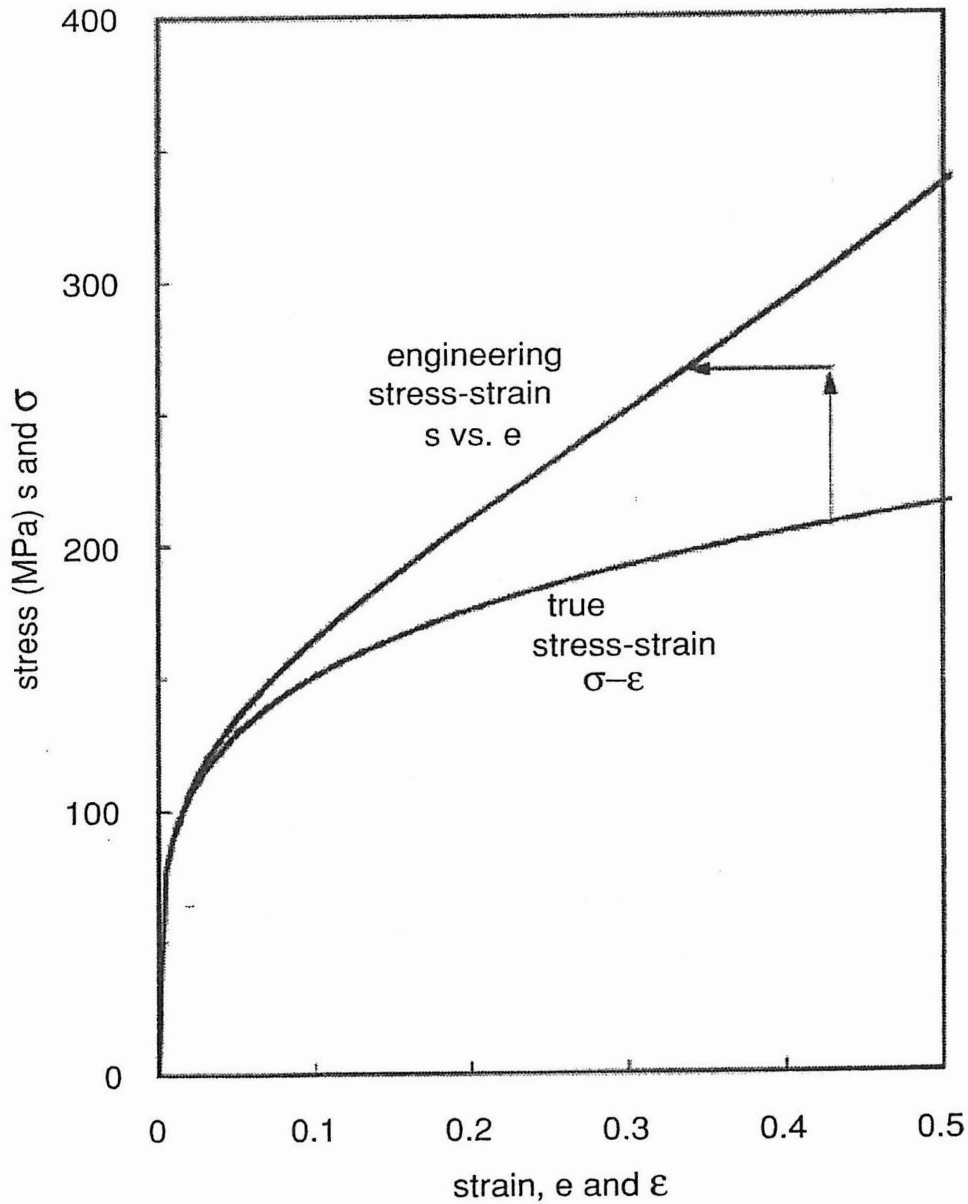


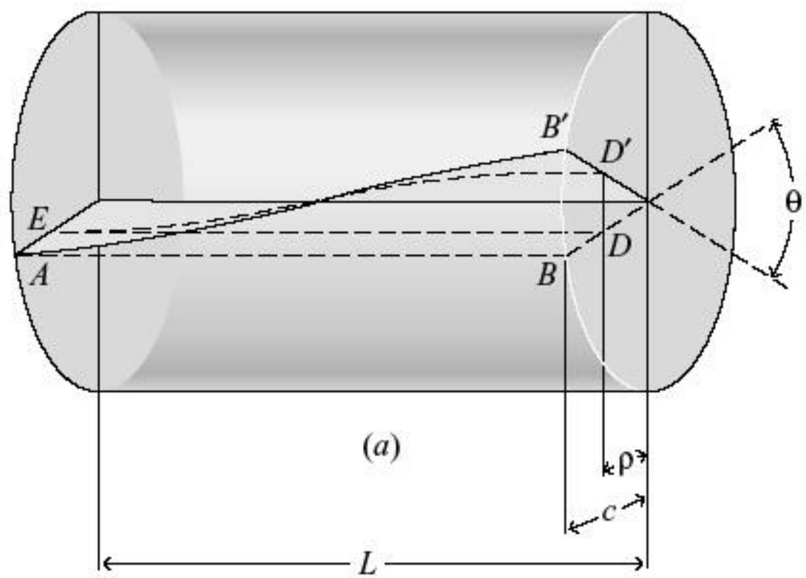
Figure 4.1. Unless the ends of a compression specimen are well lubricated, there will be a conical region of undeforming material metal at each end of the specimen. As a consequence the midsection will bulge out or *barrel*.



Torsion test

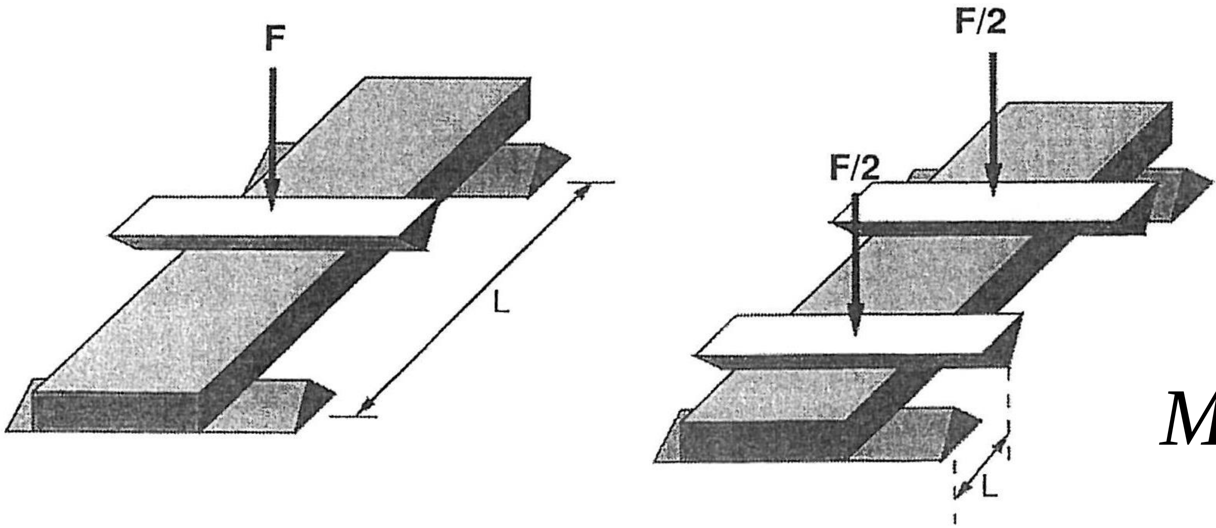
$$J_{\max} = \frac{\pi}{2} c^4$$

$$\tau_{\max} = \frac{T_{\max} \cdot c}{\frac{\pi}{2} c^4} = \frac{2T_{\max}}{\pi c^3}$$



(a)

Bending test

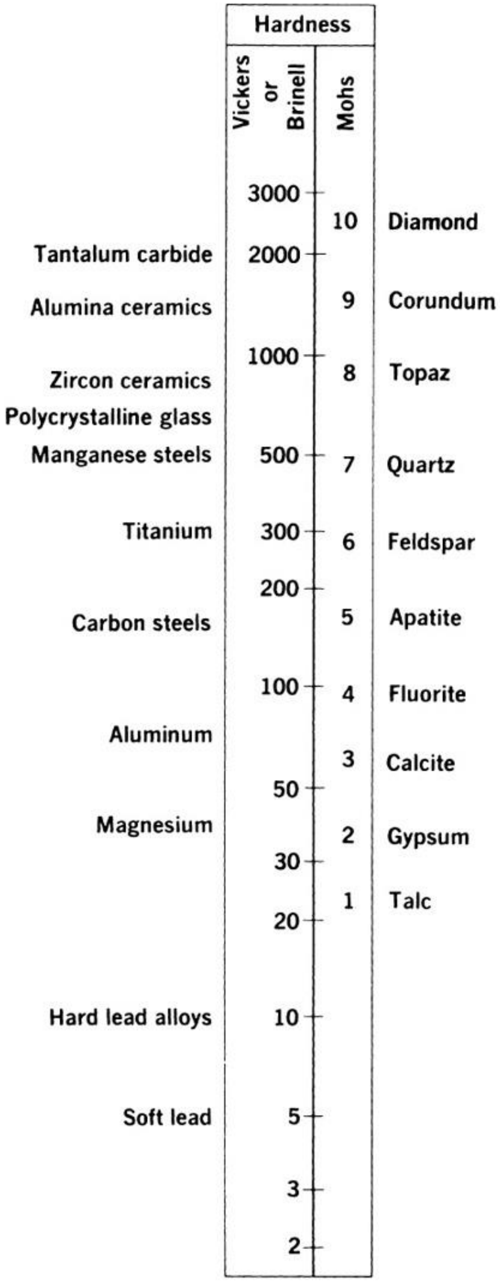


$$M_{max} = \frac{FL}{4}$$

What is the moment in three point and four point bending?

$$\sigma_{max} = \frac{M_{max} c}{I} = \frac{M_{max} \cdot h/2}{\frac{bh^3}{12}} = \frac{6M_{max}}{bh^2} = \frac{3FL}{2bh^2}$$

Hardness tests



Indentation test are divided into three classes:

Nanoindentation

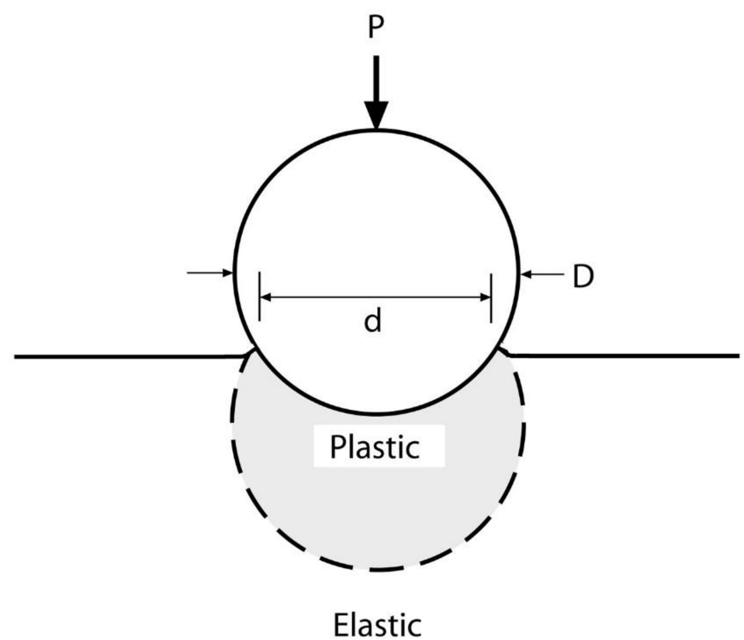
mN

Microindentation

200 gf (about 2N)

Macroindentation

Hardness cannot be considered a fundamental property of a metal. It represents resistance to plastic deformation.



Hardness tests

Projected area: Knoop, nanoindentation

Contact area: Brinell, Vickers,

Depth: Rockwell

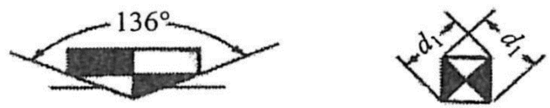
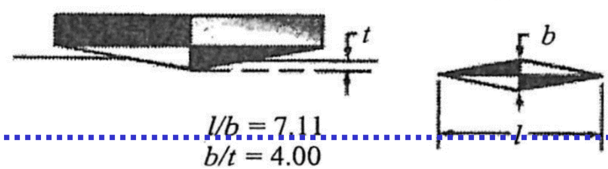
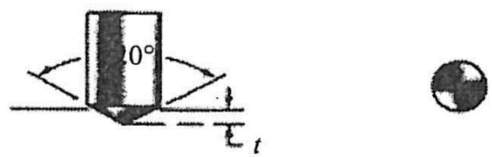
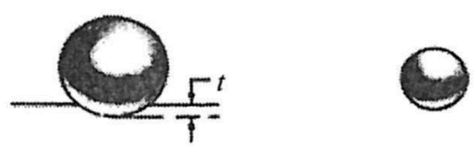
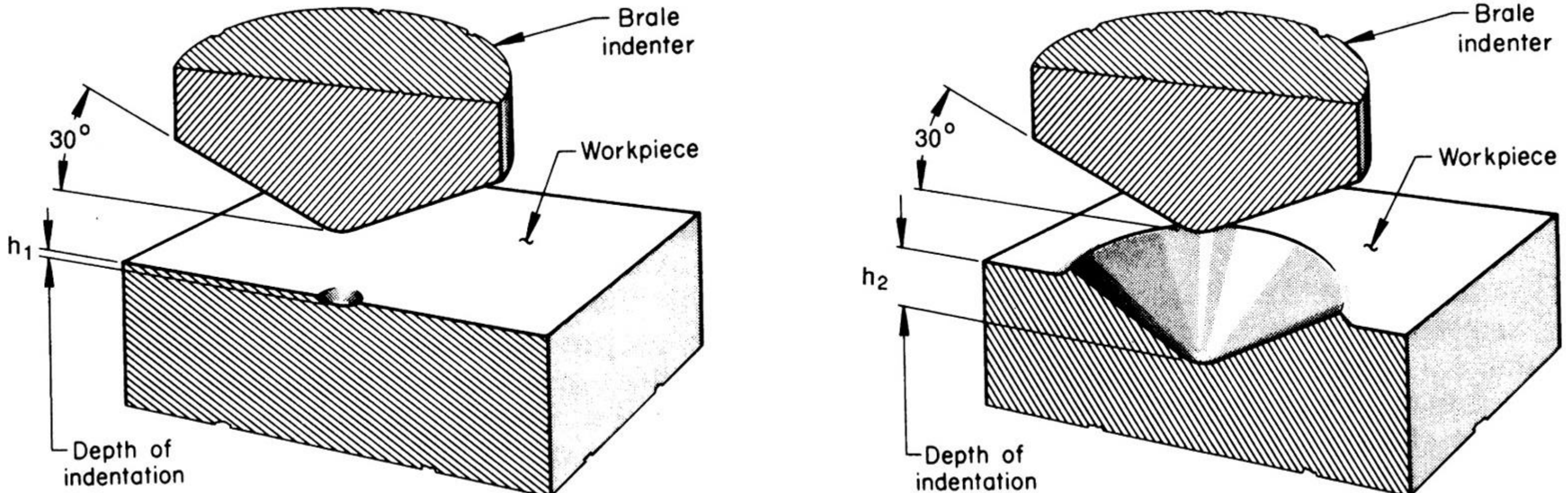
Test	Indenter	Shape of Indentation: Side View	Shape of Indentation: Top View	Load	Formula for Hardness Number
Brinell	10-mm sphere of steel or tungsten carbide			P	$BHN = \frac{2P}{\pi D(D - \sqrt{D^2 - d^2})}$
Vickers	Diamond pyramid			P	$VHN = 1.72\ P/d_1^2$
Knoop microhardness	Diamond pyramid			P	$KHN = 14.2\ P/l^2$
Rockwell A, C, D	Diamond cone			60 kg, 150 kg, 100 kg	$R_A =$, $R_C =$, $R_D =$ } 100 – 500t
B, F, G	$\frac{1}{16}$ in.-diameter steel sphere			100 kg, 60 kg, 150 kg	$R_B =$, $R_F =$, $R_G =$ } 130 – 500t
E	$\frac{1}{8}$ in.-diameter steel sphere			100 kg	$R_E =$ } 130 – 500t

Figure 4.15. Various hardness tests. From H. W. Hayden, William G. Moffat, and John Wulff, *Structure and Properties of Materials*, Vol. III, *Mechanical Behavior*, Wiley, 1965.

Rockwell test

$$HBX = M - \frac{t}{0.002} = M - 500t$$



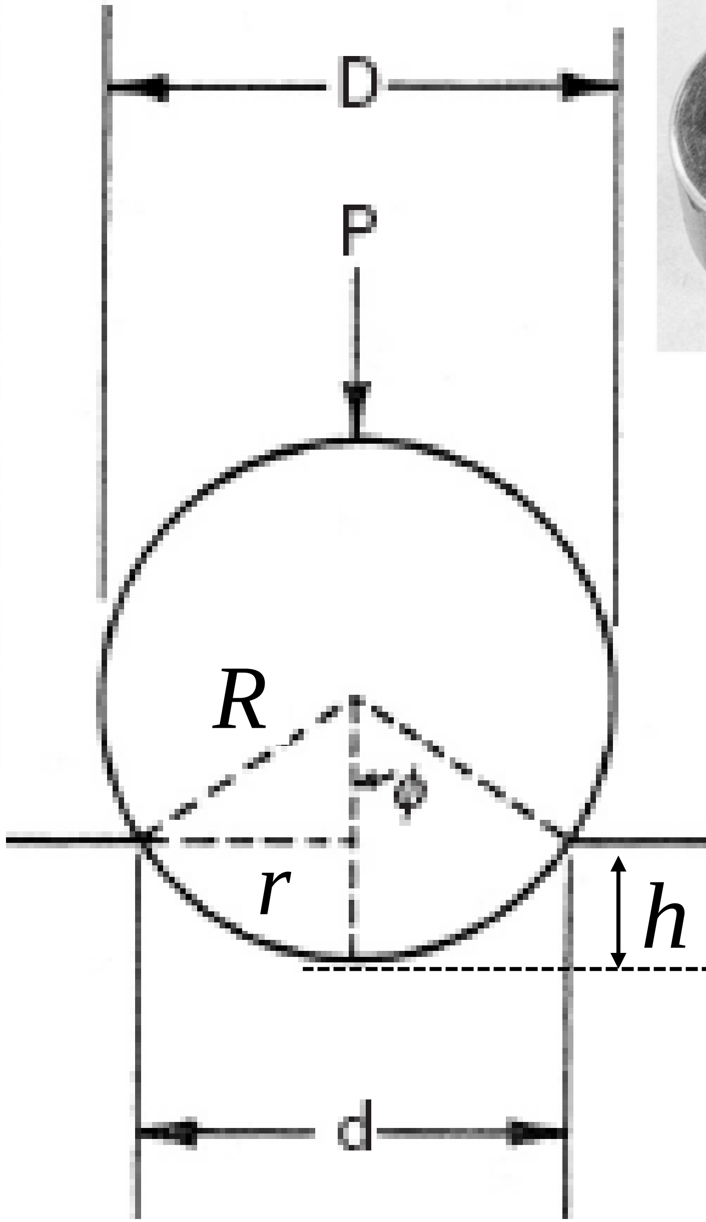
(a) Minor load (b) Major load

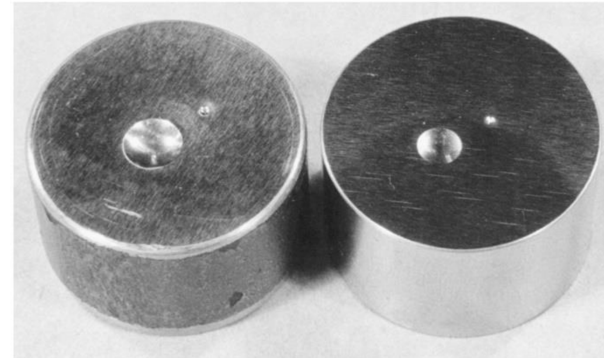
Scales for Rockwell Hardness Tester

Table 3.3 Details of the More Important Scales Available for the Rockwell Hardness Tester

Scale Designation	Type of Indenter	Major Load (kgf)	Typical Field of Application
A	Brale	60	The only continuous scale from annealed brass to cemented carbide, but is usually used for harder materials
B	1/16-in.-diameter steel ball	100	Medium-hardness range (e.g., annealed steels)
C	Brale	150	Hardened steel > HRB100
D	Brale	100	Case-hardened steels
E	1/8-in.-diameter steel ball	100	Al and Mg alloys
F	1/16-in.-diameter steel ball	60	Annealed Cu and brass
L	1/4-in.-diameter steel ball	60	Pb or plastics
N	N Brale	15, 30, or 45	Superficial Rockwell for thin samples or small impressions

Brinell test (actual area)

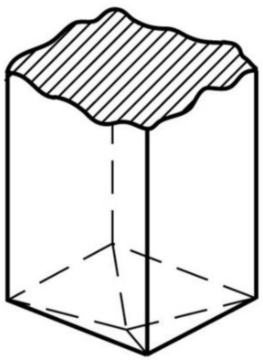




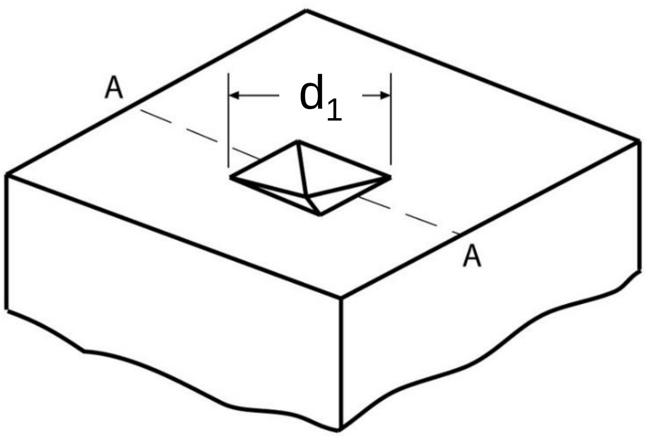
$$HB = \frac{P}{A_{actual}}$$

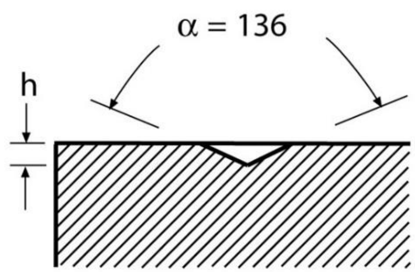
$$A_{actual} = 2\pi R \cdot h$$

Vickers Hardness Test (actual area)



$$HV = \frac{2P\sin\left(\theta/2\right)}{d_1^2} = \frac{1.85P}{d_1^2}$$





Section A-A

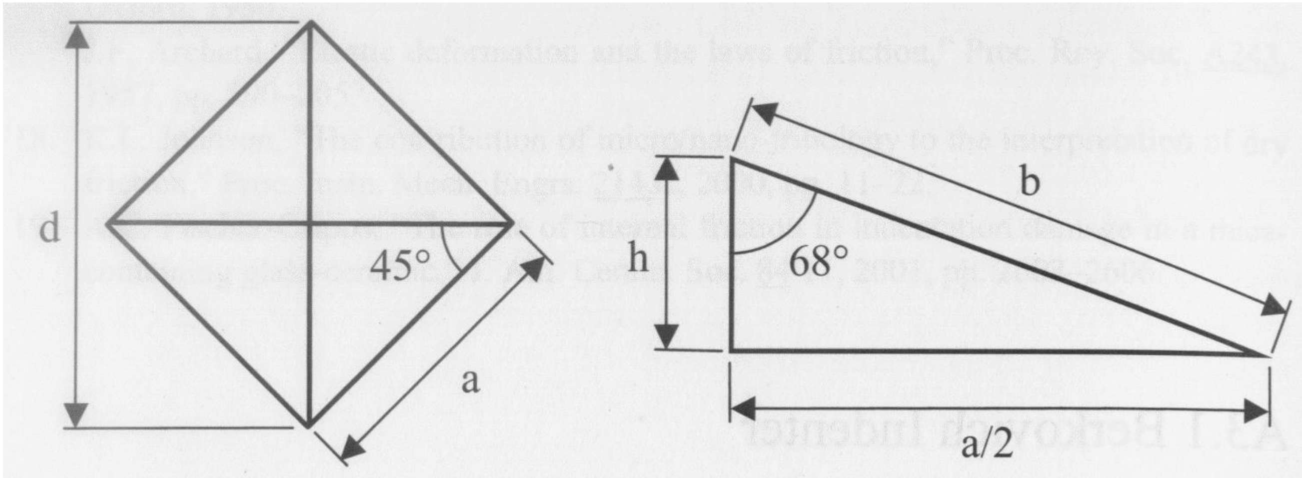
$$HV = \frac{P}{\dfrac{d^2}{2\sin 68}} = \frac{1.85P}{d^2}$$

Relationships Between Yield Stress and Hardness

$$HV = 3\sigma_y$$

For non-work-hardening materials

Vickers indenter



Projected area

Surface area

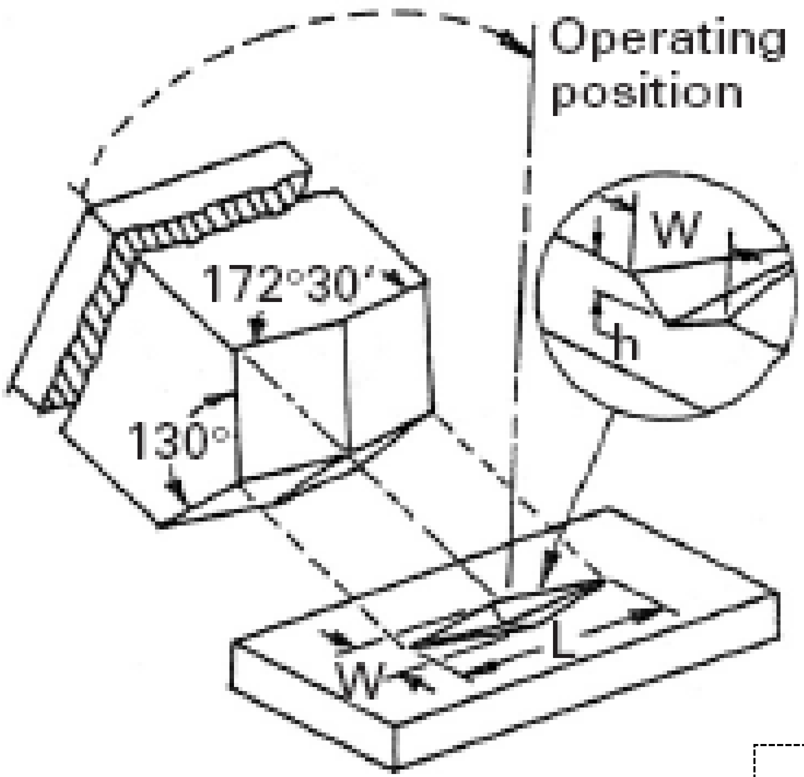
$$\sin 45^o = \frac{d/2}{a} = \frac{d}{2a}$$

$$\sin 68^o = \frac{a}{2b}$$

$$A_{proj} = a^2 = \frac{d^2}{2}$$

$$A_{surface} = 4\frac{ab}{2} = \frac{a^2}{\sin 68} = \frac{d^2}{2\sin 68}$$

Knoop Indenter (projected area)



Details of the Knoop indenter, together with its impression.

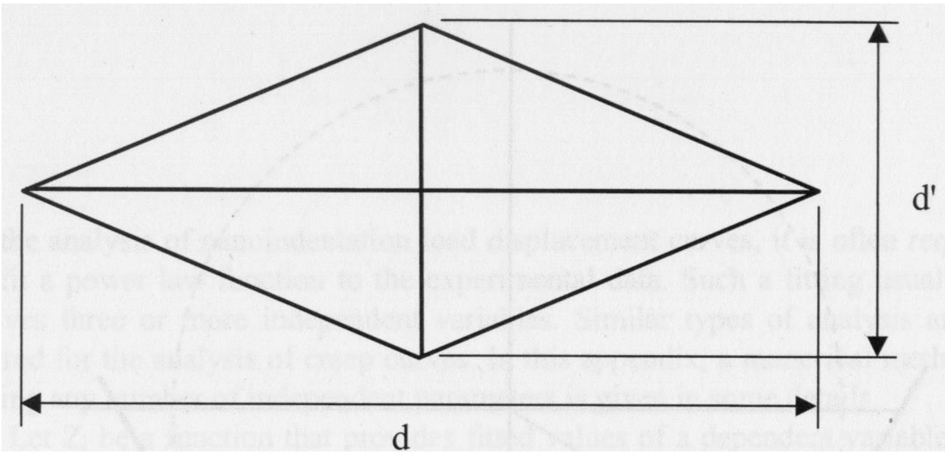
The load of kgf

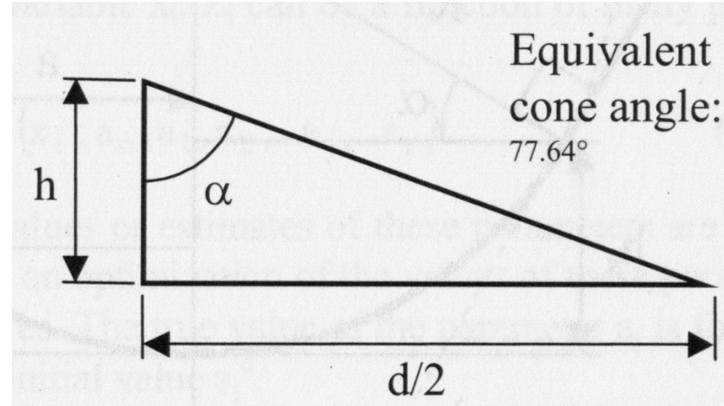
$$KHN = \frac{14.2P}{d^2}$$

The length of the major diagonal, in mm

$$KHN = \frac{P}{0.070275d^2} = \frac{14.2P}{d^2}$$

Knoop Indenter





$$\alpha_1 = 86.25^o$$

$$\alpha_2 = 65^o$$

Projected area

$$A_{proj} = 2\frac{d}{2}\frac{d'}{2} = \frac{d^2}{2}\cot\alpha_1 \tan\alpha_2$$

$$d = 2h\tan\alpha_1$$

$$d' = 2h\tan\alpha_2$$

$$d' = d\,\frac{\tan\alpha_2}{\tan\alpha_1}$$

$$A_{proj} \approx 0.070275 d^2$$

Yield strength

$$H = \left(2/\sqrt{3}\right)\left(1+\pi/2\right)Y = 2.97Y \approx 3Y$$

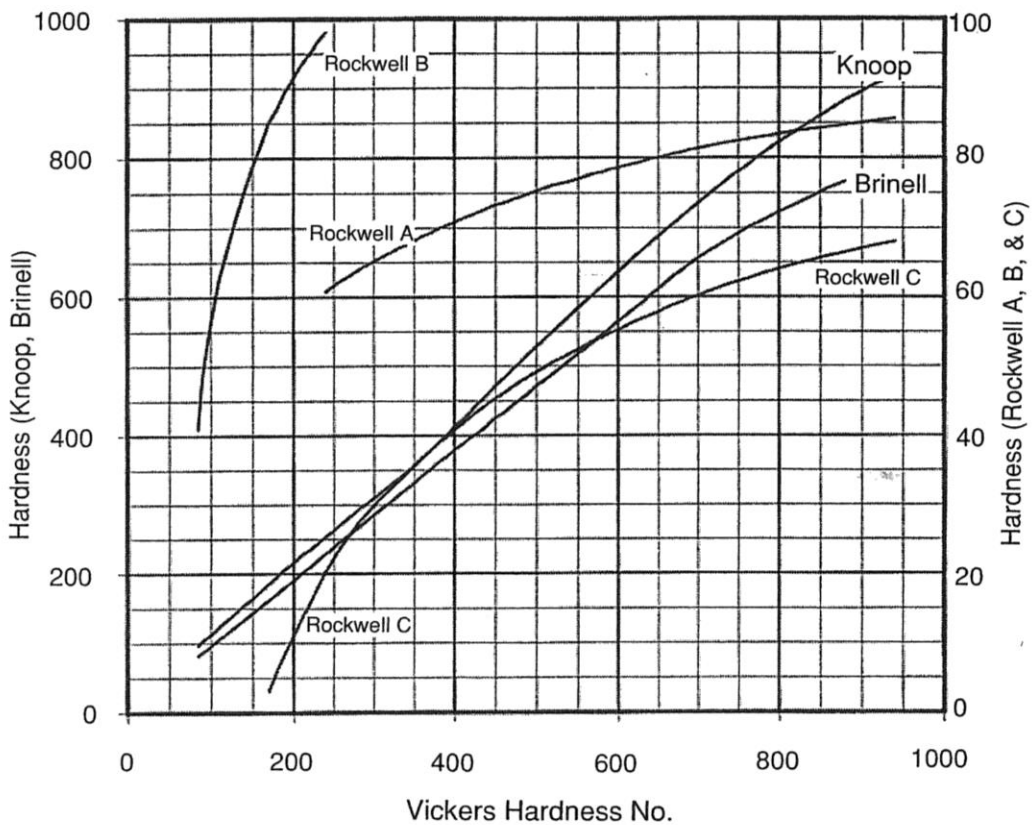


Figure 4.16. Approximate relations between several hardness scales. For Brinell (3000 kg) and Knoop read left. For Rockwell A, B, and C scales read right. Data from *Metals Handbook,* Vol. 8, ninth ed., American Society for Metals, 1985.

$$B \approx 0.95V$$

$$K \approx 1.05V$$

$$R_C \approx 100 - 1480/\sqrt{B}$$

$$R_B \approx 134 - 6700/B$$

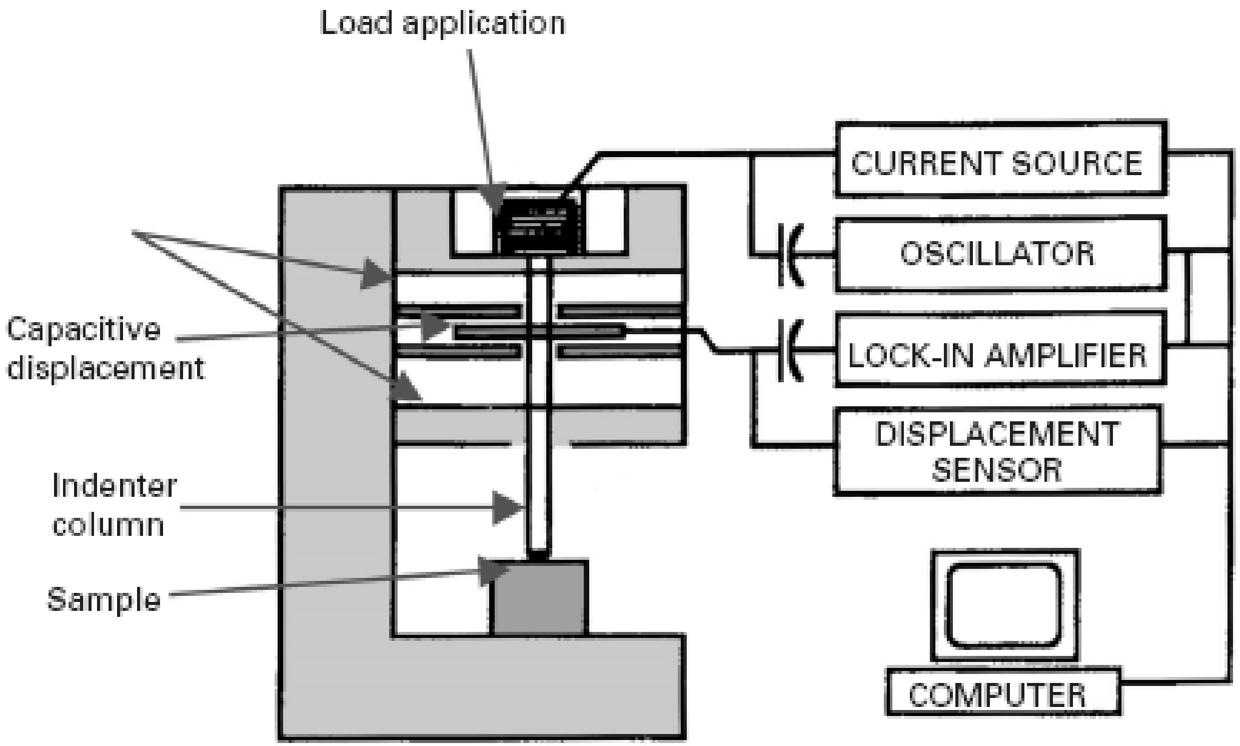
Mutual indentation hardness

The hardness as the indentation force/area, H, is proportional to its yield strength Y:

$$H = \left(2/\sqrt{3}\right)\left(1 + \pi/2\right)Y = 2.97Y \approx 3Y$$

$$H = cY$$

Nanoindenter



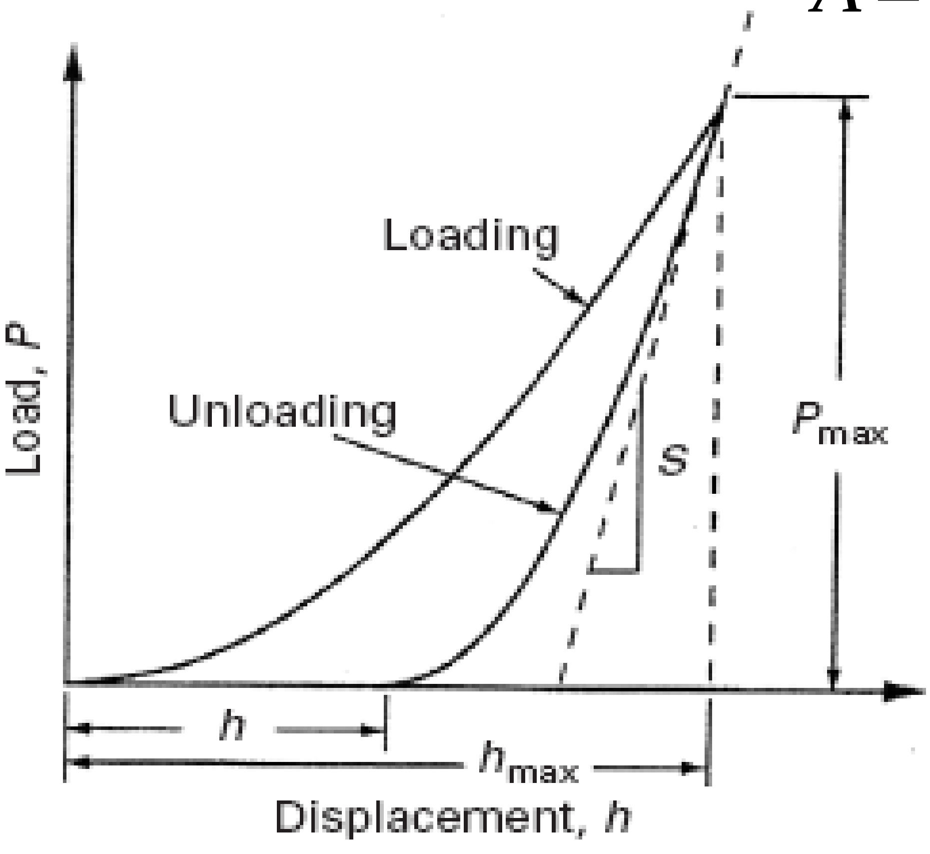
The instrument is a computer-controlled depth-sensing indentatin system measuring extremely small forces and displacement.

Load vs. Indenter Displacement

$$E_r = \left(1-\nu_i^2\right)E_i + \left(1-\nu_s^2\right)E_s \qquad H = \frac{P_{max}}{A_{proj}}$$

Projected area

$$A = a + bh_i^{1/2} + ch_i + dh_i^{3/2} + 24.5h_i^2$$



$$S = \frac{dP}{dh} = \frac{2}{\sqrt{\pi}} E_r \sqrt{A}$$

Stiffness

$$E_r = \frac{\frac{dP}{dh}}{\frac{2}{\sqrt{\pi}}\sqrt{A}}$$

Reduced modulus