HARDNESS, TOUGHNESS AND BRITTLENESS.

Hardness.—The hardness of a material is difficult to define in an exact manner; we may compare the resistance of a piece of metal to the penetration of a punch of definite shape under a gradually-applied load, and note the volume of the material displaced; or we may substitute a specific impact for the load or pressure applied gradually. Again we may compare the resistances to scratching or scoring with a conical diamond point, by determining the load necessary to produce a scratch of a definite width in accordance with the method proposed by Martens. The tensile strength, ductility, the plastic yielding as shown in torsion and bending tests are all more or less measures of hardness.

While none of these methods furnish an absolute measure of hardness, they all can be used to give a measure of hardness relative to the method of test adopted.

Static Penetration.—This method may be applied by

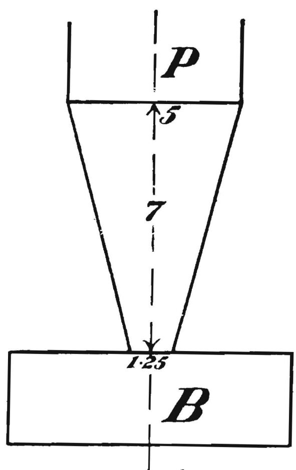


FIG. I.

causing a punch, P, to penetrate a test piece B, fig. 1, under a gradually-increasing pressure. Messrs. Calvert and Johnson used a small lever machine to apply a definite pressure to the punch P, having the dimensions shown, expresesd in millimetres, and determined the load necessary to produce an indentation of 3.5 m.m. in the metal under test in half an hour. The hardness of the metals, tested in this way, is expressed relatively to Staffordshire cast-iron, represented by 1.000.

The following table gives some of the results obtained:

TABLE I.

Metal Tested.	Load applied in k.g.	Hardness relative to Cast-iron equal 1.000.
Staffordshire Grey Cast-Iron	2176.32	1.000
Steel	2.085.64	0.958
Wrought-iron	2.062.97	0.948
Platinum	816.12	0.375
Copper	656.16	0.301
Aluminium	589.42	0.271
Silver	453.40	0.208
Zinc	398.99	0.183
Gold	362.72	0.167
Cadmium	235.77	0.108
Bismuth	113.35	0.052
Tin	58.94	0.027
Antimony	34.00	0.016

Various alloys of copper and zinc, and copper and tin, were also tested by Messrs. Calvert and Johnson.

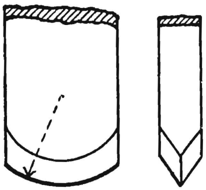


FIG. 2.

The form of punch adopted by Middleberg is shown in fig. 2. The penetration of this special form of punch will be proportional to the load applied and the length of the impression. A small lever machine, with sliding weight was employed to load the punch. This method is specially applicable to the determination of the hardness of tyres.

Prof. Unwin used as an indenting tool a straight knife edge, fig. 3. The specimen indented is a short bar of square cross-section, and the indenting tool is subjected to a pressure applied gradually.

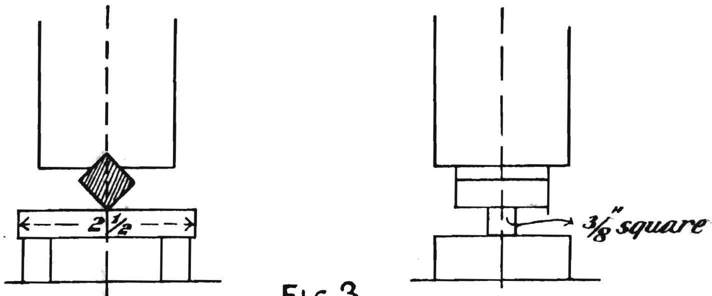


FIG. 3.

A series of observations are taken from which a constant is deduced and used to denote the hardness.

If p is the pressure per inch width of knife edge in tons, i, the indentation in inches, then $Ci = p^n$.
Where n is the slope of the line obtained by plotting the logarinthms of p and i, and C is the number denoting hardness. If the loads do not exceed that at which sensible stretching below the knife edge begins then, Unwin found that—

$$Ci = p^{1\,2}$$

The following values of C were obtained:—

TABLE II.

Mild Steel, normal	C =	143.5
,, ,, annealed	,,	141.9
,, ,, hardened	,,	186.7
Cast Steel, normal	,,	544.0
,, annealed A	,,	538.0
,, ,, B	,,	503.0
,, ,, C	,,	527.0
,, hardened in oil	,,	866.0

The apparatus employed by Kirsch is illustrated in fig. 4. The following points were determined:—

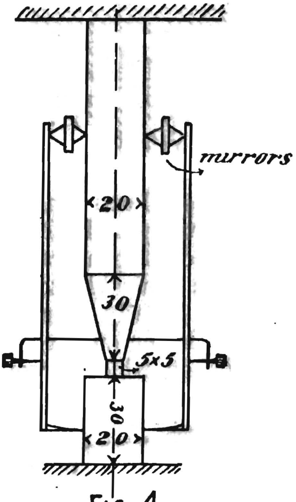


FIG. 4.

1. The limit of elasticity, identified with the load producing a permanent deformation of 0.01 m.m.

2. The limit of flindity, that is to say the first load applied for a duration of one minute, producing in this interval a flow of the body tested corresponding to a displacement of 0.

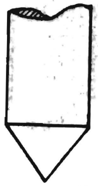


FIG. 5.

Kerpley used a conical punch (fig. 5); Rudeloff and Föppl used cylinders crossed at right angles to each other, the permanent impression made by the cylinders when pressed together is measured to compare their hardness, fig. 6.

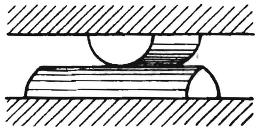


FIG. 6

Punches of hardened steel are generally used for penetration tests; the shape of the punch, the hardness condition of the surface, the method of penetration, etc., affect the results of the test. It is desirable to adopt such shapes for the punches as can be exactly reproduced by grinding. Keep used a punch, the lower surface of which had 100 small pyramids (Fig. 7), on which a weight of 25 pounds

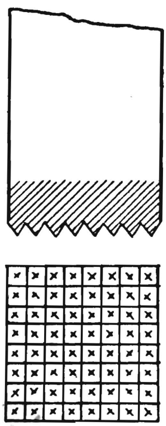


FIG. 7

was allowed to fall from a height of 3 feet (or 75 foot pounds impact). This punch was placed upon the test piece in such a manner that each successive blow produced impressions of increasing number of pyramids, and hence lesser penetration until finally the latter is just visible.

In percussion tests it must be remembered that the effect of the striking and resisting masses of the apparatus must bear identical ratios to each other.

The Rodman Punch.—(Fig. 8): This special form of punch is rigidly attached to the base or striking part of the ram in an impact testing machine.

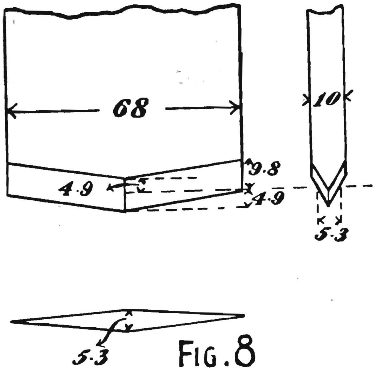


FIG. 8

The surface of the specimen to be tested is planed and polished, the steel punch is allowed to fall normally upon the surface from a given height, and the length of the indentation measured in millimetres.

The work done in producing an indentation of length l. is Wh. in kilogramme-metres.

It is assumed that the energy of the falling weight spends itself entirely in producing the indentation. The volume of material displaced is ml^3 where m varies for different forms of punch, but is constant for any one punch. It has been shown by Martel: that for all forms of pyramids, for all weights of ram, and for all heights of fall, the volume displaced of a given quality is proportional to the energy of the blow, Wh. The work or energy necestary to displace a unit volume of the material is: —$\frac{Wh}{D}$ where D is a constant characteristic of the material, and may be taken as the index of hardness, or of its resistance to indentation. To find the volume of the pyramidal displacement of the material with the Rodman punch from the measured length, multiply the cube of the length by 0,0009413. (log 4.97375) or the volume equals $0.0009413l_r^3$. The Rodman punch is very convenient, and the volume displaced by any punch can readily be computed.

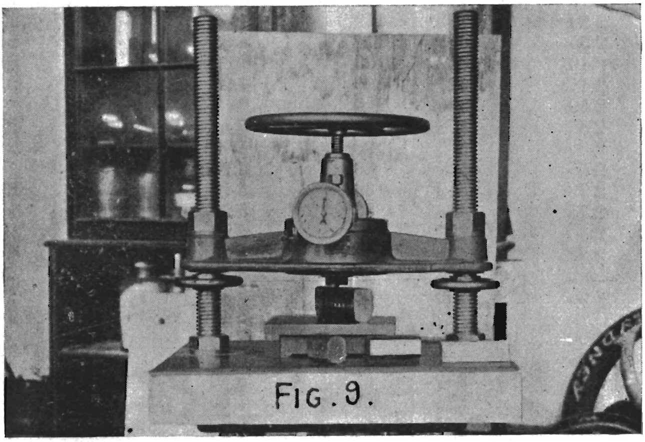
The following table gives values of D (degrees of hardness on the Martel scale) in kilogramme-millimetre units for various metals:—

TABLE III.

Metals.	Degree of Hardness. Kilogramme-millimetre Units.
High Carbon (Diamond) Steel, hardened in Oil ..	613
" " " not hardened ..	460
Medium Steel, hardened in oil	455 – 300
Hoop Steel, water hardened	330 – 295
Rolled Wrought Iron	226
Hammered Wrought Iron	238
Cast Iron for Guns	300 – 208
Copper, rolled	156
Zinc, rolled	77
Tin, cast	33
Lead, Cast	9

Brinell's Method.—M. J. A. Brinell's method of determining the hardness of metals consists in using a small ball of tempered steel 10 m.m. in diameter, pressed gradually into the metal specimen, with a force of 3000 k.g. for iron and steel, and 500 kg. for the softer metals, such as copper, zinc, and tin, and their alloys. The pressure is maintained for two minutes, and is divided by the area of the surface of the impression made in the specimen. The quotient gives the hardness expressed in kilogrammes per square millimetres. The Brinell apparatus has been designed in various forms, and is extensively used in Europe. The form used by the author is illustrated in fig. 9.

It consists of a specially designed hydraulic press, in which the pressure is applied by means of a hand-wheel and screw. Two hydraulic gauges indicate the pressure applied, which should be callibrated from time to time. The photo shows a sample subjected to the indentation of the steel ball 10 m.m. in diameter. The following Table IV. has been prepared to facilitate the calculations of hardness when the diameter of the impression has been determined.



If the diameter of the impression is 4.55 m.m., with 3000 kg., the table IV. gives the hardness number as 174. If only 500 kg. has been applied the table IV. gives the hardness number as 29.1.

It is necessary to measure the diameter of the impression very carefully, and the best method of doing this is to use a Zeiss measuring microscope. It will generally, however, be sufficiently accurate to determine the diameter to $\frac{1}{100}$ of a millimetre, and this can be done by means of the apparatus shown in fig. 10.

M. H. Le Chatelier devised a glass rule (fig. 11) which also enables the diameter to be determined to $\frac{1}{10}$ m.m. with the naked eye.

This apparatus has been used also for the determination of the tensile strength of metals, by multiplying the

TABLE IV.

Table for the determination of hardness by Brinell's method.

Diameter of the Impression, mm.	Hardness Number for the Pressure, in k.g.		Diameter of the Impression, mm.	Hardness Number for the Pressure, in k.g.	
	3000	500		3000	500
2	946	158	4.50	179	29.7
2.05	898	150	4.55	174	29 1
2.10	857	143	4.60	170	28.4
2 15	817	136	4.65	166	27.8
2.20	782	130	4.70	163	27 2
2.25	744	124	4.75	159	26.5
2 30	713	119	4.80	156	25.9
2 35	683	114	4.85	153	25.4
2.40	652	109	4.90	149	24.9
2 45	627	105	4.95	146	24.4
2.50	600	100			
2.55	578	96	5	143	23.8
2.60	555	93	5.05	140	23.3
2 65	532	89	5.10	137	22.8
2 70	512	86	5.15	134	22.3
2.75	495	83	5.20	131	21.8
2.80	477	80	5.25	128	21.5
2.85	460	77	5.30	126	21
2.90	444	74	5.35	124	20.6
2.95	430	73	5.40	121	20 1
			5.45	118	19.7
3.00	418	70	5.50	116	19.3
3.05	402	67	5.55	114	19
3.10	387	65	5.60	112	18.6
3.15	375	63	5.65	109	18.2
3 20	364	61	5.70	107	17 8
3.25	351	59	5.75	105	17.5
3.30	340	57	5.80	103	17.2
3.35	332	55	5.85	101	16.9
3 40	321	54	5.90	99	16.6
3.45	311	52	5.95	97	16.2
3 50	302	50			
3 55	293	49	6.00	95	15.9
3.60	286	48	6.05	94	15.6
3.65	277	46	6.10	92	15.3
3.70	269	45	9.15	90	15 1
3.75	262	44	6 20	89	14.8
3 80	255	43	6.25	87	14.5
3.85	248	41	6.30	86	14.3
3.90	241	40	6.35	84	14
3.95	235	39	6.40	82	13 8
			6.45	81	13.5
4.00	228	38	6.50	80	13 3
4.05	223	37	6.55	79	13.1
4.10	217	36	6.60	77	12.8
4.15	212	35	6.65	76	12.6
4.20	207	34.5	6.70	74	12 4
4.25	202	33 6	6 75	73	12 2
4.30	196	32.6	6.80	71.5	11.9
4.35	192	32	6.85	70	11 7
4.40	187	31.2	6.90	69	11.5
4.45	183	30.4	6.95	68	11.3

hardness number obtained by a certain constant. In order to ascertain the relation of the hardness obtained by Brinell's method, and the tensile strength obtained in the usual way, the author prepared specimens cut from the ends of test pieces which had been tested in tension and obtained the results recorded in the following table. These show a fairly constant ratio in steel and iron of the same kind.

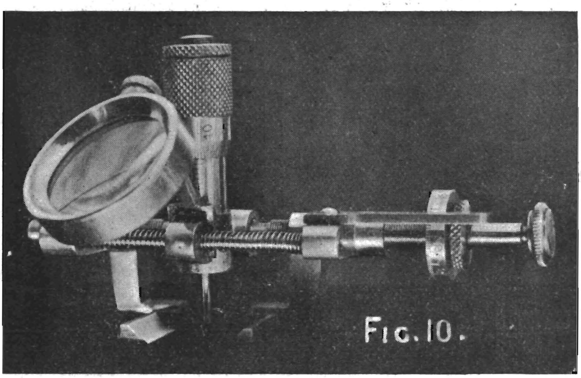


Fig. 10.

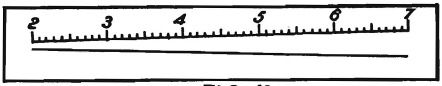


FIG. 11

The results recorded in the following table were obtained by Mr. W. D. Donkin, B.E., in connection with a thesis on Brinell's method, and the method has been continued in connection with tension tests whenever convenient.

TABLE V.

Table showing the hardness of various kinds of iron and steel tested by Brinell's method, and the relationship between hardness and tensile strength.

Material.	Tensile Strength in tons per sq. in. equal t.	Hardness across the Fibre equal h.	Value of $\frac{t}{h}$ across the Fibre.*	Hardness with the Fibre h'.	Value of $\frac{t}{h'}$ with the Fibre.
Wrought-iron Axles	21.85	126	.173	130	.168
" "	21.59	138	.156	145	.149
" "	21.49	124	.173	138	.156
" "	21.72	128	.170	134	.162
Mean ...	21.26	129	.168	136.7	.158.7
Iron Rail, re-rolled	18.40	150	.123	178	.104
" "	21.50	176	.120	193	.100
Wrought-iron used in various Bridges in New South Wales ...	23.4	144	.162	159	.147
	22.4	141	.159	157	.143
	22.5	145	.155	167	.135
	22.4	160	.140	159	.141
	22.1	136	.162	156	.141
	22.6	130	.174	160	.142
	21.2	125	.169	126	.156
	21.2	140	.151	137	.155
	21.9	116	.189	140	.156
	22.2	137	.162	165	.134
Mean ...	22.19	137.4	.162	153.6	.145
Structural Steel	28.9	170	.170	...	...
" "	30.2	149	.203	...	...
" "	25.3	141	.180	...	...
" "	25.6	140	.183	...	...
" "	27.0	140	.193	...	...
" "	25.8	140	.184	...	...
" "	24.9	137	.182	...	...
" "	25.6	134	.191	...	...
Mean ...	26.7	143.	.186	...	...
Axle Steel, Cammell	34.00	167	.202	...	...
" "	36.50	168.5	.216	...	...
" Vickers	33.95	205	.165	...	...
Mean ...	34.8	180	.194	...	...
Tyre Steel, Cammell	49.81	235.6	.211	...	...
" "	49.25	235.0	.211	...	...
Krupp Carbon Steel	38.2	185.5	.206	...	...
" "	38.8	180	.215	...	...
3 per cent. Nickel Steel, Krupp ...	45.17	230	.196	...	...
" " " ...	45.25	241	.188	...	...
6 " " " ...	43.50	227.5	.191	...	...
" " " ...	47.90	227.5	.211	...	...

* Across the Fibre in the above Table means that the direction of the pressure applied is perpendicular to the direction of rolling the material.

If, in a piece of structural steel, the hardness number is found to be 144, the tensile strength will be about 26.8 tons per square inch. It will be observed from the foregoing results that there is a relationship between the Brinell hardness number and the tensile strength, which is approximately constant for steel of the same kind.

In regard to the results obtained by using balls of different diameters and pressures, it was found by Benedicks that a constant hardness number is obtained by multiplying the Brinell number by the fifth root of the diameter of the ball; also that by plotting curves representing the relation of the hardness number to the load producing it in the case of lead and soft steels, the value of the ordinates for the same abcissal bear a constant ratio to each other, thus proving that a comparable hardness number may be obtained by determining them all at the same pressure as originally suggested by Brinell.

Tests made by Brinell with a constant pressure of 2000 kg.: where H eq. hardness number, and P eq. radius of ball:—

TABLE VI.

Radius of ball equal *P* millimetres.	Steel Number.					
	1		5		12	
	H	$H\sqrt[5]{P}$	H	$H\sqrt[5]{P}$	H	$H\sqrt[5]{P}$
37.5	107	130	208	271	315	410
5.00	99	136	201	277	306	422
7.50	95	142	178	266	272	407

Tests made by Benedicks with a constant pressure of 500 kg., with a special steel containing 1.40 per cent. of carbon:—

TABLE VII.

P	H	$H\sqrt[5]{P}$
1.60	306	366
2.49	288	346
2.99	277	344
3.97	263	346
5.00	253	350
6.37	230	346

Professor Martens' method of testing the scoring hardness.

Martens has adopted the scoring or scratching method of determining hardness, and has developed the method first applied by Turner. Fig. 12 illustrates Martens' apparatus:—

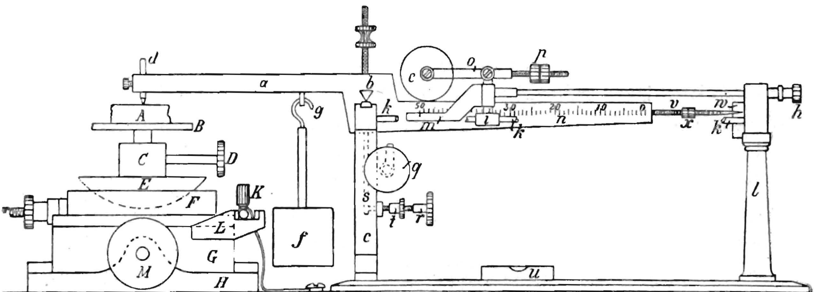


FIG. 12.

A diamond with a conical point is carried on the end of a lever *a*, and can be loaded by means of a poise weight moved along the graduated scale *n*. The specimen A, to be scratched, is attached to the plate B, carried on a slide rest, F, which is moved slowly under the diamond point. Martens' system consists in the determination of the load in grammes on the diamond, which produces a scratch of a definite width, 10μ eq. 0.01 m.m. (0.00039 in.), or simplifying the method by taking the value of the width of line in μ produced by a definite load on the diamond. Actually the approximate load necessary to produce a certain width of scratch is selected, and groups of five scratches are made under varying loads, until the desired width of scratch is certainly contained in one of these groups. The different average width of scratches and the loads producing them are plotted on a diagram, as ordinates and abscissœ.

From these curves the average line is drawn, which gives the load which would produce the line, having a width of $10\mu = 0.01$ m.m. (fig. 13).

The widths of the lines must be carefully measured by means of a microscope provided with micrometers.

The following table shows the values obtained by Martens:—

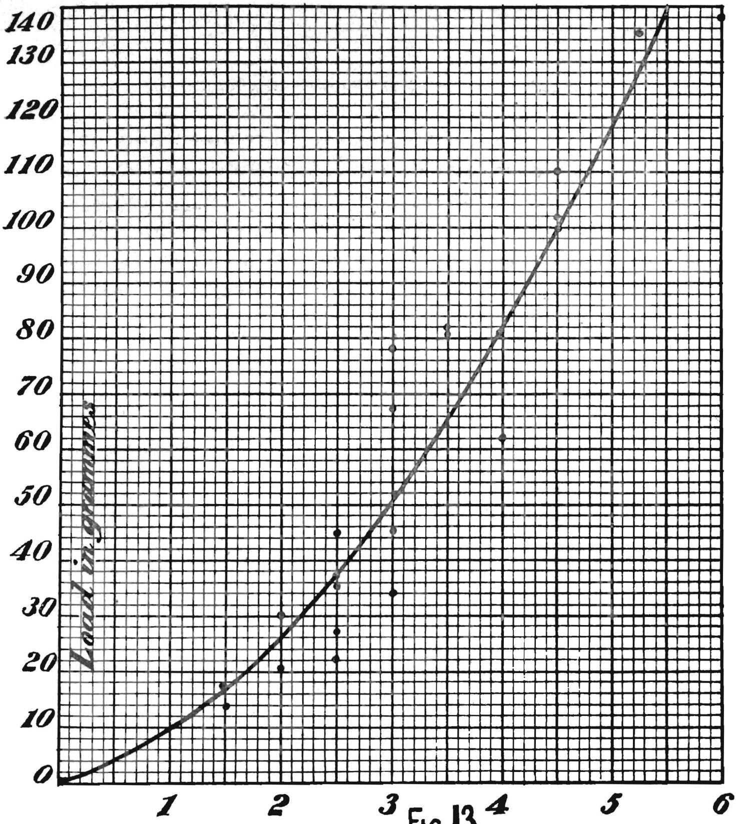


FIG. 13

TABLE VIII.

Scoring Hardness of Materials compared with Moh's scale.

Material.	Composition.	Scoring Hardness.	Moh's.
Lead	P6	16.8	1.5
Tin	Sn.	23.4 – 28.2	2—3
Alloy	Cu. Sn_5 ; 97:903	36.4	2—3
"	Cu. Sn_4 ; 119:881	37.8	2—3
Copper	Cu.	34.3—39.8	3
Zinc	Zn.	42.6	...
Alloy	Cu. Sn_3 ; 152:848	30—44.6A	2—3
"	Cu. Sn_2 ; 212:788	21.8—48.7A	2—3
Brass	...	44.7—52.8	...
Nickel	Ni.	55.7	...
Alloy	Cu. Sn. ; 350:650	62.5A	3—4
"	Cu_{25} Sn. ; 932:68	67.5	3
Soft Steel	...	70.8—76.5	...
Alloy	Cu_{15} Sn. ; 890:110	78.0	3
"	Cu_{20} Sn. ; 915:85	81.6	3—4
"	Cu_{10} Sn. ; 843:157	82.5	3—4
"	Cu_2 Sn. ; 482:518	83.0	4
Glass	...	135.5	5—5.5
Hard Steel	...	137.5—141.0	6—6.5

A. Containing hard and soft spots.

Toughness and Brittleness.—Toughness and brittleness, like hardness, are difficult to define, as there is no absolute measure of these qualities. Pitch is tough when deformed slowly, and brittle when broken by impact. Glass is brittle at ordinary temperatures, but becomes tough when heated. The following measures of toughness have been proposed:—

(*a*) The difference between the ultimate strength of the material and the yield point.

(*b*) The ratio of the yield point to the ultimate strength, or that of the ultimate strength to the yield point.

(*c*) The Elongation, or the Contraction of area at fracture.

(*d*) The ratio of the ultimate strength to the yield point multiplied by the Elongation per-cent divided by 100.

Martens suggests that tension tests should be used, and the method, *d*, adopted to show the relative properties of materials. Thus, toughness is expressed:—

$$T = \frac{\sigma_r\ \epsilon\ \%}{\sigma_y\ 100}$$

If the ultimate tensile strength of steel is 28 tons per sq. in., the yield point, 16.8 tons per sq. in., and the elongation 25 per cent., then:—

$$T = \frac{28 \times 25}{16.8 \times 100} = 0\ 412$$

Plasticity.—Soft inelastic tough materials are usually plastic, and can be subjected to great changes of shape without fracture; they can be rolled, drawn into wire, and generally subjected to great permanent deformations. The ratio of the toughness to the yield point has been proposed as a measure of plasticity:—

$$P = \frac{T}{\sigma_y} \times 10 = \frac{0.412}{16.8} \times 10 = 0.245$$

for the steel, giving a toughness of 0.412.