

AN ACCURATE METHOD OF DETERMINING
THE HARDNESS OF METALS, WITH PARTICULAR
REFERENCE TO THOSE OF A HIGH DEGREE
OF HARDNESS.*

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[Selected for Publication.]

Before undertaking to commence an investigation of this description, it is, of course, most desirable that the term "hardness" should be clearly understood and well defined. Unfortunately, up to the present, there is no universally approved or standardized quantitative definition for "hardness," and it therefore follows that until the arrival of this definition, all investigations in search of accurate methods for hardness testing will be in the future, as in the past, more or less unsatisfactory owing to the uncertainty of requirements. As it is not, however, the object in view at present to attempt to introduce a standard definition for hardness, but rather to increase the accuracy and reliability in methods and apparatus for testing, the Authors have in their investigations assumed that "Hardness is proportional to the load necessary to produce a constant sized impression," this being in their opinion the most rational and generally approved expression for hardness at present available, in spite of it undoubtedly lacking certain desirable qualifications which become necessary in order to make it really "definite."

Theoretically, it should be possible to deduce the load to give a constant impression from the Brinell formula, since if the hardness

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[THE I.MECH.E.]

numerals obtained were truly relative, they should be proportional to the loads giving identical impressions. It is well known that this is not the case, but the Authors have found that, by a suitable modification to the Brinell formula, it is possible to obtain truly relative hardness figures, from which may be calculated the load required to give a constant impression. Such a method has the advantage that no special apparatus is required, and that one impression only at a constant load is necessary.

So many formulæ for hardness have been put forward and subsequently contradicted that some hesitation is felt in promulgating yet another or in approaching the matter at all from a theoretical standpoint. The formula given for this modification is therefore quoted entirely on the understanding that it has been obtained experimentally. In order to make the explanation more simple and concise, the full description of the apparatus and methods of arriving at the formula and carrying out the calibrations is omitted from this account, but will be found in the various Appendixes.

The test is carried out as in the ordinary Brinell method, with a 10 mm. ball, and the modified hardness numeral is calculated according to the formula :—

$$\text{Brinell Hardness Number at 1,000 kg.} \propto \left(0.9 + \frac{0.4}{d^2}\right),$$

where d is the diameter of the impression in millimetres.

The load of 1,000 kg. was selected because it gave neat impressions capable of very accurate measurement. The curve resulting from this formula is shown in Fig. 1, and is compared with that resulting from the ordinary Brinell formula.

From this new formula also may be calculated the load required to give any size of impression, but 2.5 mm. was selected as the constant impression for the same reason given above. The factor for use in obtaining this size of impression is 5.18567, and the resulting curve is shown in Fig. 2. It will be appreciated that the most searching check in these calculated figures is to ascertain whether the calculated load does actually produce the constant impression. The various shaped points shown on Fig. 2 refer to results arrived at independently on a variety of materials, and it will be seen that the differences are extremely small even on the harder materials, where errors of measurement, etc., may be expected to influence the results to an undue extent. The results, therefore, fully confirm the accuracy of the formula within the limits of experimental error.

It was still found, however, that the results obtained in the higher ranges were far from satisfactory. There appears to be no

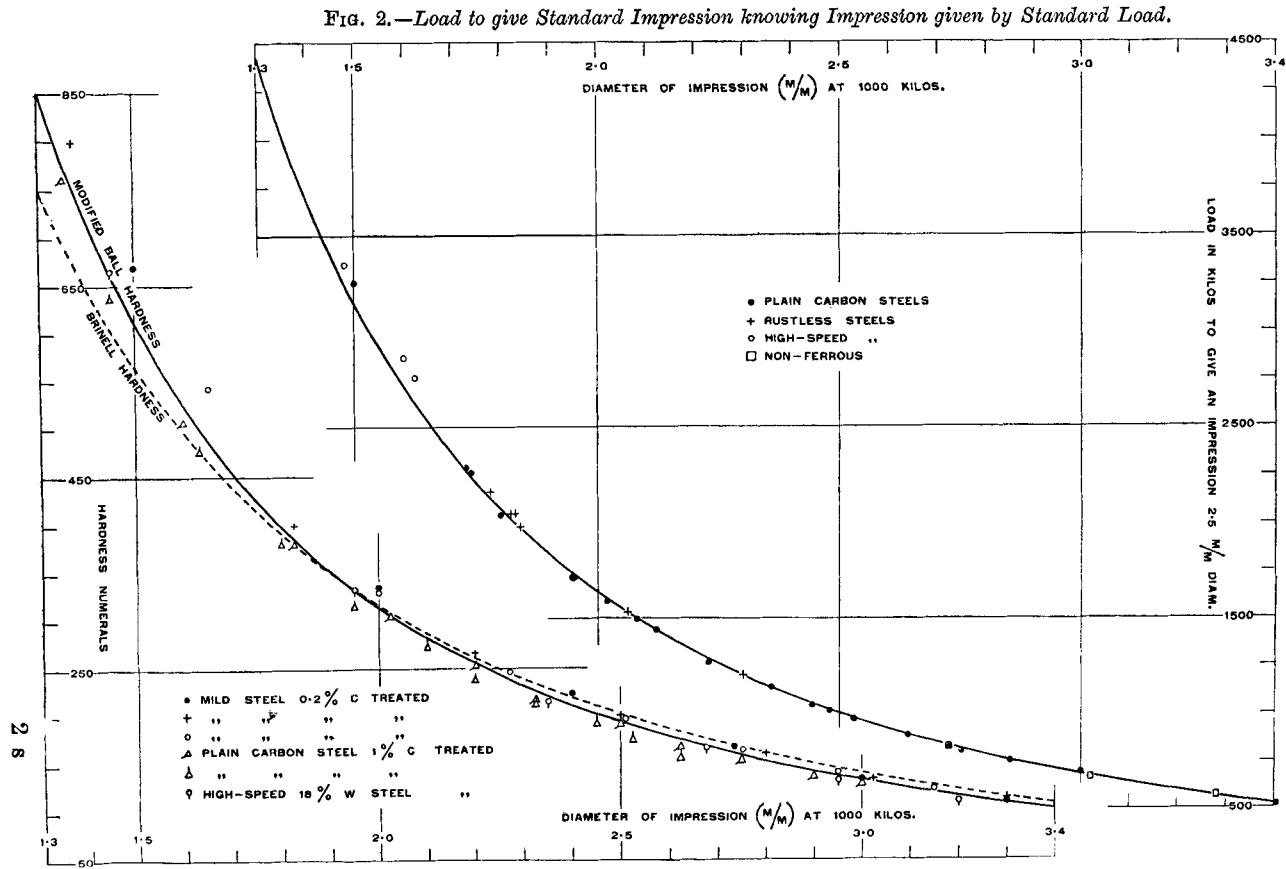


FIG. 1.—Brinell and Modified Ball Hardness Numerals, knowing Diameter of Impression at 1,000 kilograms.

FIG. 4.—No. 1 Diamond. Load to produce 2.6 Impression knowing Impression produced by 100 kilograms.

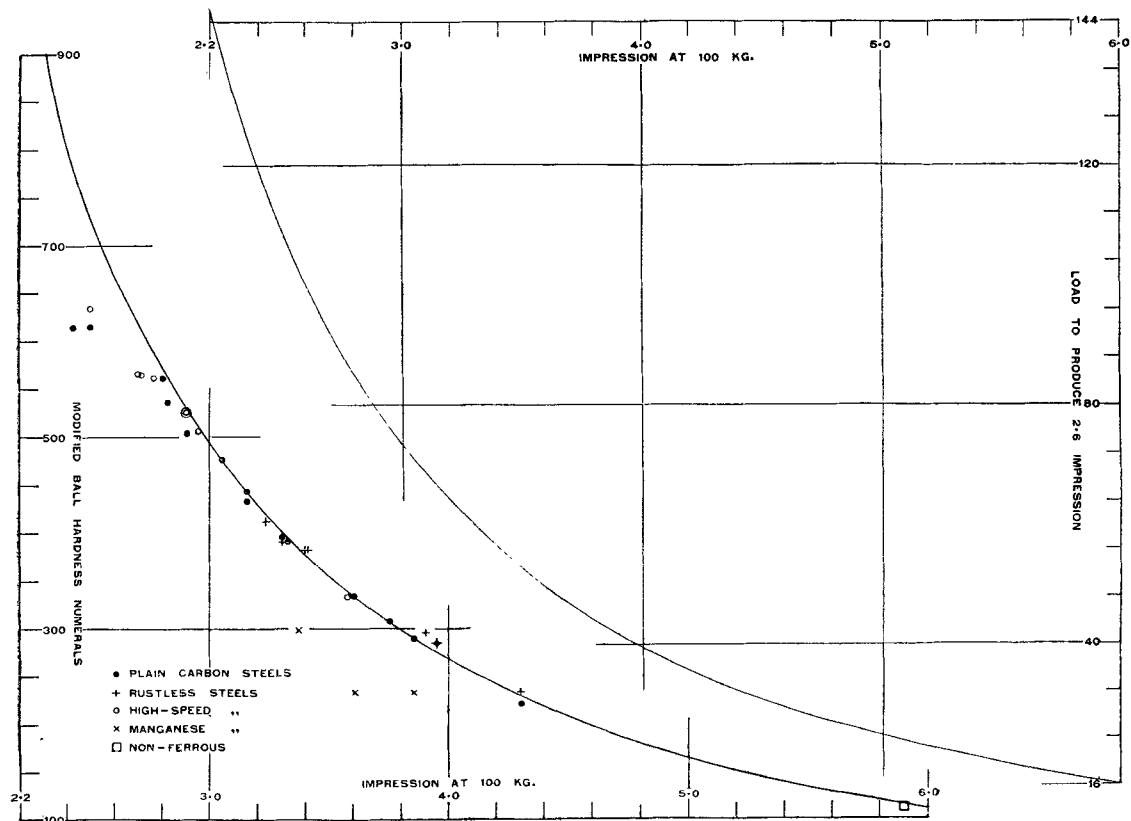


FIG. 3.—No. 1 Diamond. Modified Ball Hardness Numerals knowing Impression produced by 100 kilograms.

FIG. 6.—No. 2 Diamond. Load to produce 2.6 Impression knowing Impression produced by 100 kilograms.

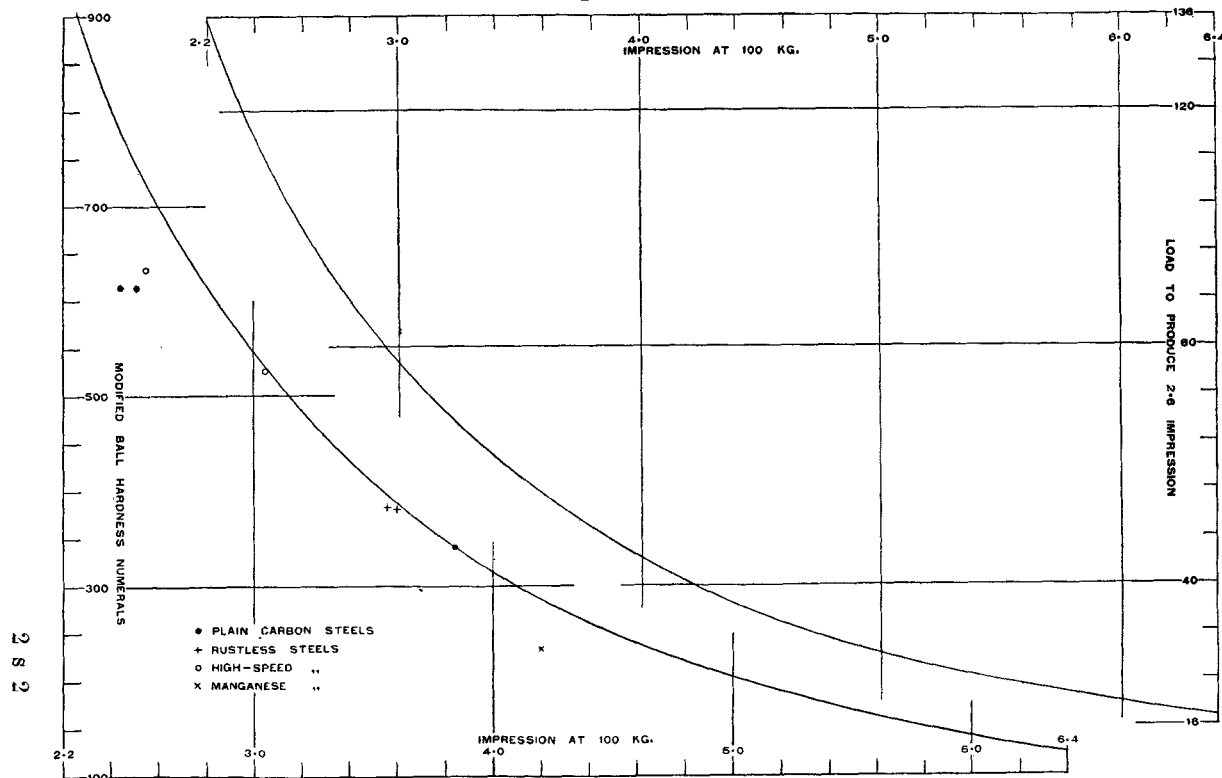


FIG. 5.—No. 2 Diamond. Modified Ball Hardness Numerals knowing Impression produced by 100 kilograms.

doubt at all that this is due to the excessive deformation of the ball, and Shore,* in confirming this and correlating the Brinell and Scleroscope Scales, was able to obtain more accurate results by means of a spherical diamond, the hardness of which, of course, greatly exceeds that of the hardest steel, and is consequently not liable to undue deformation. This method, however, was found to be impracticable for general use owing to the difficulty of obtaining and grinding a diamond to a perfect hemispherical surface, besides which breakages were frequent, and the impressions were difficult to measure owing to their limited size.

The Authors found that it was possible to use an uncut diamond with a natural pyramidal point, and to calibrate it so as to obtain the hardness figures of materials over the complete range. Since the diamonds are not accurately formed to any specific shape, each must be calibrated separately. The results of such a calibration are shown in Figs. 3, 4, 5, and 6, in which the dimensions of impressions are correlated with the modified Brinell Hardness Numerals, and the loads required to give standard diamond impressions on two different uncut diamonds. It will be appreciated that, as before, the most searching checks on the accuracy of these figures would be to ascertain whether the calculated load does in all cases produce the standard impression, and whether the hardness figures arrived at from this Table agree with those obtained on the same material by means of the ball test. Numerous tests were carried out, and it was found that the errors in the dimensions of the standard impressions in all cases fell within 1 per cent, thus proving the accuracy of the load curves within experimental limits.

The various shaped points shown on Figs. 3 and 5 refer to results where the Modified Ball Hardness Numerals obtained by means of the ball have been plotted against the size of impression obtained with the diamond. It will be seen that the bulk of the points agree very closely with the curve. A possible explanation of the nonconformity of manganese steels is given below, but apart from such materials, the only other exceptions are on the steels of a very high degree of hardness.

The fact that the diamond readings are found to be substantially correct on the lower ranges, and that the loads to produce constant impressions are accurately predicted on all materials of whatsoever hardness, lead to the inference that the hardness figures obtained from the diamond are substantially correct on the higher ranges also, and that the hardness figures obtained by the ball are incorrect

* Journal of the Iron and Steel Inst., 1918, No. 2, p. 59.

above about 550 M.B.H. This figure corresponds to about 525° Brinell, and although rather lower than is generally suspected, it closely confirms Shore's findings with a diamond ball.

Up to date, the most reliable method of obtaining hardness figures above this point has been by means of this spherical diamond. Such a diamond was not at the Authors' disposal, but it is of interest to note that the standard block supplied with the scleroscope was found by means of the diamond to be 705 Brinell Hard. Shore gives 685° as corresponding to 100 sclero, a difference between diamond point and diamond ball of only 3 per cent. In view of the double correlation, this would appear to be remarkably well within the limits of experimental error. It should be clearly understood that only one test is necessary in order to arrive at these results, but it is found that the application of the load required to give a constant impression acts as a very efficient check on readings, both with ball and diamond. It should also be made clear that in conducting this investigation, a very considerable number of check tests were carried out, and it was found that in every case the load to produce the constant impression was accurately predicted.

The use of modified ball hardness numbers has the further advantage that, by their aid, it is possible to form more accurate estimates of the maximum stress than with the Brinell numbers, as only one factor is required over the range 30-90 tons for plain carbon steels. With the Brinell numbers the points lie on a curve, while with the modified ball numbers they lie on a straight line which passes through the origin, and a single factor of 0.23 suffices for the correlation, Fig. 12 (page 640). It will be seen that a much more accurate relationship is thus established. It will be apparent, however, that it is a very simple matter to correlate these figures with the Brinell hardness numbers, and the operator is not therefore in any way confined to the use of M.B.H. numbers.

With the diamond test the load applied is very light and the impression shallow; it is, therefore, very sensitive to the surface hardness of the material. Thus it very easily detects the presence of a hard or soft skin. Wide differences between the hardness numerals obtained by the ball and diamond impressions on manganese steel are shown in Figs. 3 and 5, which illustrate this point, the surface of the steel having apparently been unavoidably hardened in the preparation of the test-piece. On other materials a hard or soft skin may be detected by taking one test on the surface and another after removal of 0.01 inch or thereabouts. For the same reasons, the test may be very advantageously applied for exploring the hardness of materials either superficially or internally. Specimens which have

been prepared for microscopical examination may also be tested in marked areas with the greatest ease, and for ordinary case-hardened work the impressions are so shallow that they do not penetrate the case unless the latter is very thin. While the investigations have all been carried out with rough or natural diamonds, the Authors do not wish to suggest that the use of a specially prepared and cut diamond would not be a material improvement, since a more constant shape of impression may thereby be obtained.

Summary :—

1. By knowing the impression given by a standard load, it is possible, by means of a formula, to obtain ball hardness figures, which are proportional to the load required to give a standard impression.

2. This ball test fails at about 525 Brinell or 550 by modified ball hardness.

3. Such modified ball hardness numerals may be determined by means of an uncut diamond with a natural pyramidal point, over the whole range of hardness.

Conclusion.—The Authors appreciate the disadvantage attendant upon the introduction of a new standard of hardness, but they venture to suggest the general use of modified ball hardness numerals on lines similar to those described above, or still better, the adoption of iron or some suitable element as a standard of unit hardness. The choice of such standard should, of course, be left in the hands of a competent committee. Attempts to use electrolytic iron in the manner indicated above have not been entirely successful, owing to the very coarse structure in the softest condition ; but the principle offers such advantages that it justifies further research in this direction.

The Authors wish to take this opportunity of expressing their indebtedness to Messrs. Vickers, Ltd., in whose laboratories at Erith the whole of the investigation was carried out.

The Paper is illustrated by 6 Figs. and 5 Appendixes with 6 Figs.

APPENDIX I.

Description and Method of using the Apparatus employed for the application of the Diamond Tests.

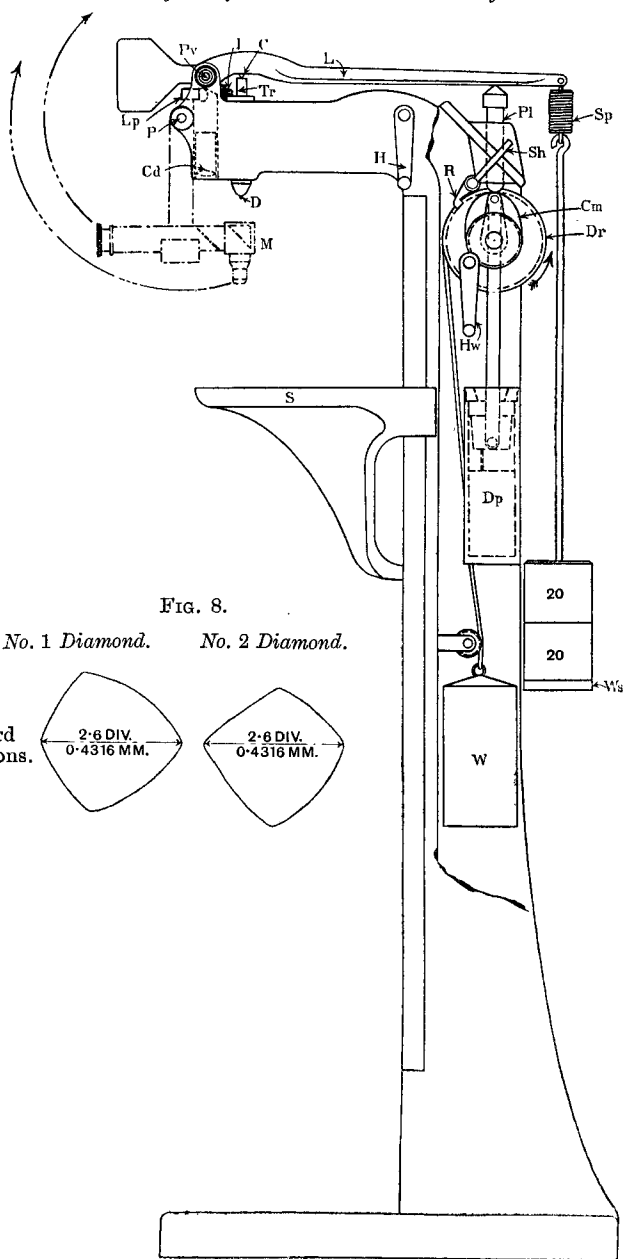
The apparatus used for these experiments was practically identical to that illustrated in Fig. 7. The work is placed upon the stage "S," the microscope "M" being swung on pivot "P" through 180°, so as to be clear of the stage. By means of the handle "H," operating through bevel gearing and an elevating screw, the stage is raised until the test-piece makes contact with the diamond "D," and elevates same with its holder to the correct position shown by the coincidence of the lines on the indicator "I." When in this position, the point of the cone "C" is just clear of its seating in the thrust rod "Tr." The opposite end of this rod rests in a seating immediately above the diamond; the object of this arrangement is to eliminate side thrust between the diamond holder and its guide.

The load is applied to the diamond through the thrust rod and cone which is attached to a lever "L," pivoted at "Pv." This lever gives a 10 to 1 ratio for the weights which give the maximum load, and are placed on the weight support "Ws," which hangs from the end of the lever "L." If the starting handle "Sh" is depressed and released the weight "W" is allowed to fall and rotate the drum "Dr" to which it is connected by means of a cord wound round the same. This drum carries a cam "Cm," which controls the fall and rise of the plunger "Pl," by means of which the load is applied to and released from the diamond as the drum makes one revolution.

The speed of rotation is controlled by a dashpot "Dp," the piston of which carries an adjustable needle valve and a non-return valve, which closes on the downward and opens on the upward stroke. The drum therefore rotates slowly through 180° and then increases its speed through the remaining 180°, when it is brought to a stop by the pawl "R," which engages in a slot cut in the periphery of the drum and is controlled by the starting handle. When the drum rotates thus, the load applied gradually increases to a maximum, (controlled by the weights on the weight support), over a period of 15 seconds, remains so for 30 seconds, and is then released in 5-10 seconds. The stage "S" is now lowered about 3.5 inches, and the microscope swung back into position where it is correct for reading the impression on the test-piece.

A lamp "Lp," and condenser "Cd" supply the necessary vertical illumination. A fine adjustment is supplied for focussing the

FIG. 7.—Diagram of Diamond Hardness Testing Machine.



microscope, but is not shown in the illustration. The weight "W" is raised by rotating the handle "Hw," and the machine is then ready for another test. The spring "Sp," and a spring plunger (not shown) inside the plunger "Pl," eliminate the possibility of errors due to inertia. A suitable ball holder is supplied, by means of which a small ball may be substituted for the diamond.

APPENDIX II.

Conditions under which the Tests were carried out.

All loads were applied for a period of 30 seconds, which was found to be more than sufficient to produce a maximum impression.

Ball Tests.—The ball impressions were made with a 10 mm. ball, and were measured in millimetres by means of the ordinary microscope supplied with the Brinell testing machine, and also with a Cambridge reading microscope calibrated to 0.01 mm.

Diamond Tests.—The diamonds selected were of the ordinary type as used for emery wheel setting, and were chosen for their natural pyramidal points. They were not cut or otherwise shaped, but were mounted direct in mild steel holders in the ordinary manner. A load of 100 kg. and impression of 2.6 divisions were adopted as standards, as under these circumstances the impressions are capable of accurate measurement and the loads are never excessive.

The standard sized impressions for the two diamonds used are illustrated on Fig. 8. The diamond impressions were measured across one axis by means of a Swift microscope fitted with vertical illuminator and micrometer eyepiece, one large division of which corresponds to 0.166 mm. Thus a standard impression of 2.6 divisions = 0.4316 mm.

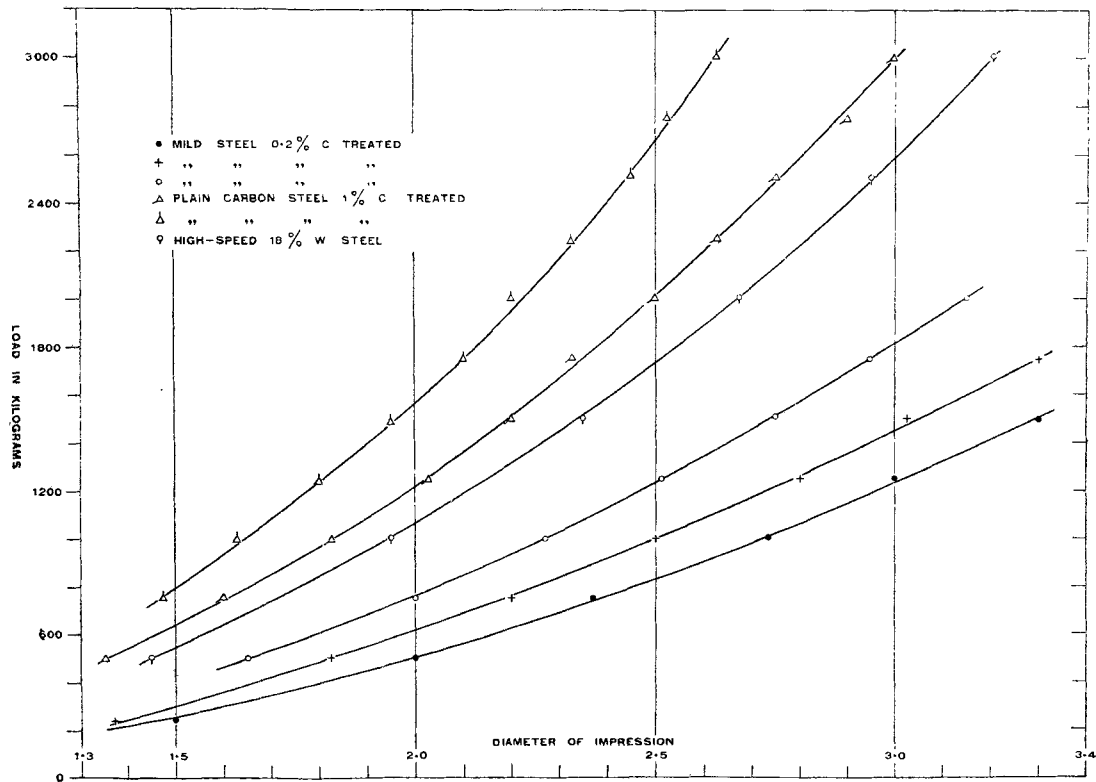
APPENDIX III.

Description of the Method of arriving at the Formula for Modified Ball Hardness Numerals, and of deducing the Load required to give a constant Impression.

An incremental series of loads was applied to a number of materials, the dimensions of impressions being noted and plotted as shown in Fig. 9.

By Brinell's Formula :— $H = \frac{P}{A}$.

FIG. 9.—Load/Impression Curves for determining the Formula for Modified Ball Hardness Numerals.



For any one material, the ratio $\frac{P}{A}$ should be a constant, and in comparing two materials, the hardnesses should be proportional to the loads giving identical impressions.

$$\text{i.e. } \frac{H_2}{H_1} = \frac{P_2}{P_1} \therefore H_2 = \frac{P_2}{P_1} H_1.$$

As is well known, this does not hold good. But let it be assumed that H for any one material equals a constant and is given by the Brinell hardness at 1,000 kg. Then, by substituting for P_2 , H_1 , and P_1 , a number of hardness figures are obtained which for each material are strictly proportional. If the diameters of the impressions are plotted against the hardness numerals so obtained, they will be found to lie approximately on a smooth curve. If also the diameters of the impressions are plotted against the hardness numerals given by the ordinary Brinell formula, it will be found that the two curves do not coincide, and it is found that the formula which satisfies the new curve is:—

$$\text{Hardness numeral} = \text{Brinell hardness at 1,000 kg.} \times \left(0.9 + \frac{0.4}{d^2}\right).$$

These curves are shown in Fig. 1 (page 625), and the various shaped points refer to hardness numerals obtained from a number of different materials, as shown above. It will be appreciated that, owing to the assumption that the Brinell formula is correct at 1,000 kg., many errors have arisen, and the points therefore lie only fairly approximately near the line.

It is claimed, however, that the hardnesses obtained by the above formula are relative, and they should therefore be proportional to the load required to produce any given size of impression. The standard ball impression selected was, as already stated, 2.5 mm. Reference to the formula shows that if a piece gives this impression at 1,000 kg., the hardness is:—

$$200 \times \left(0.9 + \frac{0.4}{2.5^2}\right) = 192.8 \text{ approx.}$$

Then if a piece is H_2 Modified Brinell hard at 1,000 kg., the load required to give a 2.5 impression is:—

$$\frac{1,000 \times H_1}{192.8} = H_1 \times 5.18567.$$

Hence, if a load of 1,000 kg. result in an impression of d_1 mm. in diameter, the hardness of the material is:—

$$\text{Brinell hardness at 1,000 kg.} \times \left(0.9 + \frac{0.4}{d_1^2}\right) \text{ modified ball,}$$

and the load required to produce a 2.5 mm. impression is :—

$$\text{Brinell hardness at 1,000 kg.} \times \left(0.9 + \frac{0.4}{d_1^2}\right) \times 5.18567.$$

The resulting curve is shown in Fig. 2 (page 625).

APPENDIX IV.

Calibration of Diamond to give Load for Constant Diamond Impression and Modified Ball Hardness Numerals.

An incremental series of loads is applied with a ball to a homogeneous material of hardness H_1 , the diameters of the impressions being noted. If the diameters and loads be plotted against one another, the load giving any predetermined impression is known.

Suppose that the load required to give a 2.5 mm. impression is K kg., and that on applying a load of 1,000 kg. to a material of unknown hardness H_2 , an impression d_2 be obtained, then it may be found from the above curve that a load of B kg. would be required to produce such an impression on the original material of hardness H_1 .

$$\text{Then} \quad \frac{H_2}{H_1} = \frac{1000}{B},$$

and to obtain a 2.5 mm. impression on H_2 ,

$$\frac{H_2}{H_1} = \frac{X}{K} \therefore \frac{1000}{B} = \frac{X}{K},$$

$$\therefore X = \frac{1000 K}{B} \text{ kg., where K and B are known.}$$

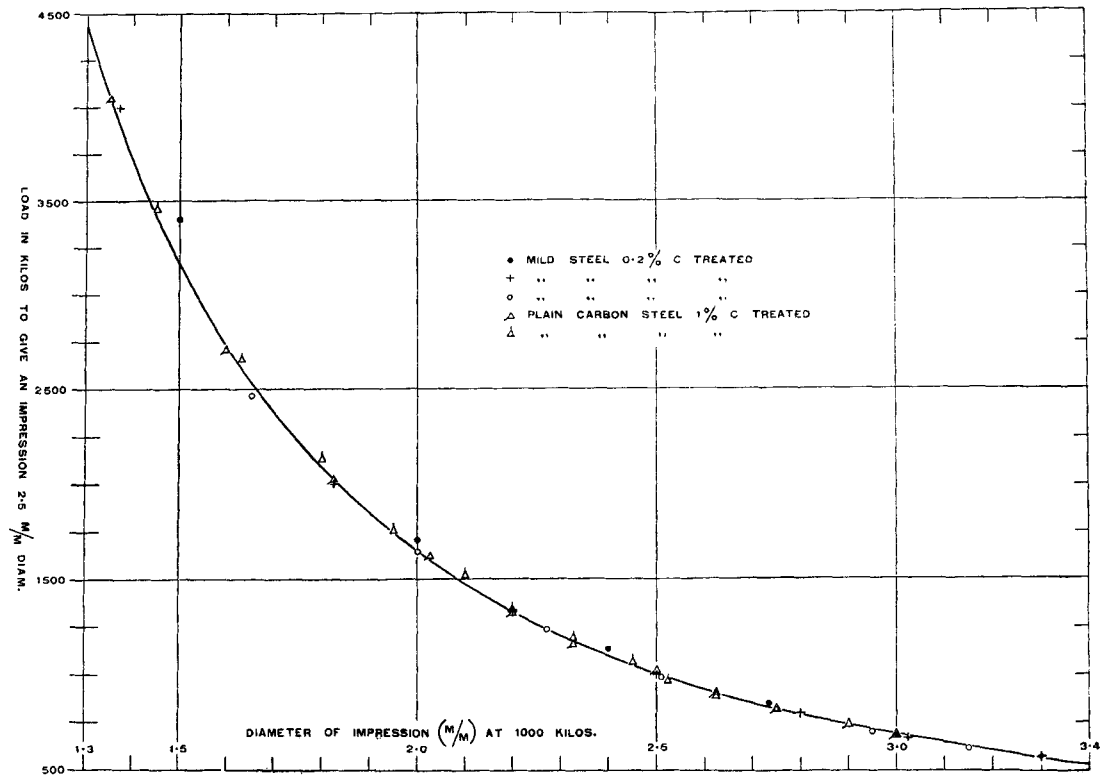
On substituting, a series of kilogram loads is obtained for corresponding diameters. This substitution was carried out with the materials which were tested in connexion with Appendix III, the results being plotted in Fig. 10.

The curve obtained from the formula :—

$$\text{Load to give 2.5 imp.} = \text{Brinell hardness} \times \left(0.9 + \frac{0.4}{d^2}\right) \times 5.18567,$$

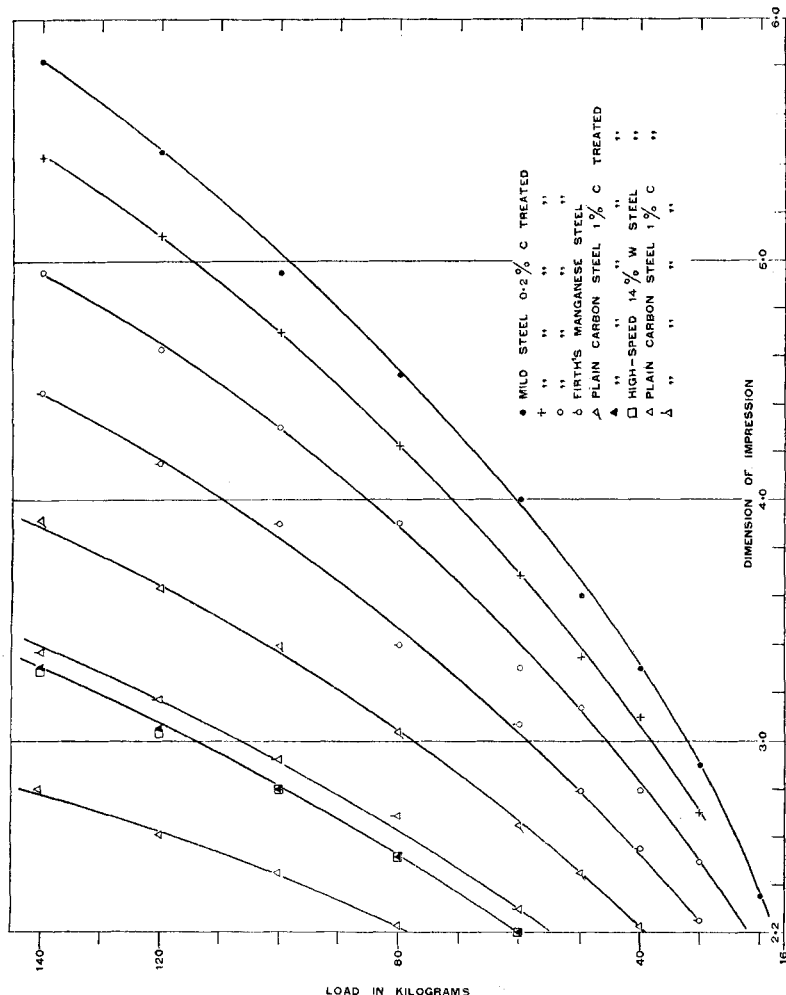
is also plotted, and it will be seen that the points all lie very close to the line indeed, thus showing that by means of an incremental series of loads on a single homogeneous material, it is possible to deduce the loads, giving a constant impression knowing the impression given by a constant load on any other. This has held good on all materials tested up to date.

FIG. 10.—The Curve obtained from the Formula compared with Points given by Incremental Series of Loads on various Materials.



A similar incremental series was carried out on a homogeneous material A exactly as was done with the ball, but using the diamond,

FIG. 11.—Load/Impression Curves for Calibrating No. 1 Diamond.



and it may be shown in the same manner that the load required to give a 2.6 impression on C (another material) is given by:—

$$\frac{100 \times P_1}{P_2} \text{ kg.}$$

Where :—

100 kg. is the standard load applied to C,

P_1 is the load which gives a 2.6 impression on A.

P_2 " " " an impression on A of the same size as that given on C by 100 Kg.

Now, these loads are proportional to the modified ball hardnesses, so that if the hardness of A is known, the modified ball hardness may be correlated with the diameters thus :—

$$\begin{aligned} \frac{\text{Hardness of C}}{\text{Hardness of A}} &= \frac{\text{Load to give constant impression on C}}{\text{Load to give constant impression on A}} \\ \therefore \text{Hardness of C} &= \frac{\text{Hardness of A} \times \text{load to give constant impression on C}}{\text{Load to give constant impression on A}} \\ &= \frac{\text{Hardness of A} \times 100 P_1}{P_2 \times P_1} \\ &= \frac{\text{Hardness of A} \times \text{Standard Load of 100 kg.}}{\text{Load to give an impression on A of same size as that given on C by 100 kg.}} \end{aligned}$$

Series of tests such as the above were carried out on several materials of different hardness, and the steps are shown in Figs. 3, 4, 5, 6 (pages 626-7), and Fig. 11.

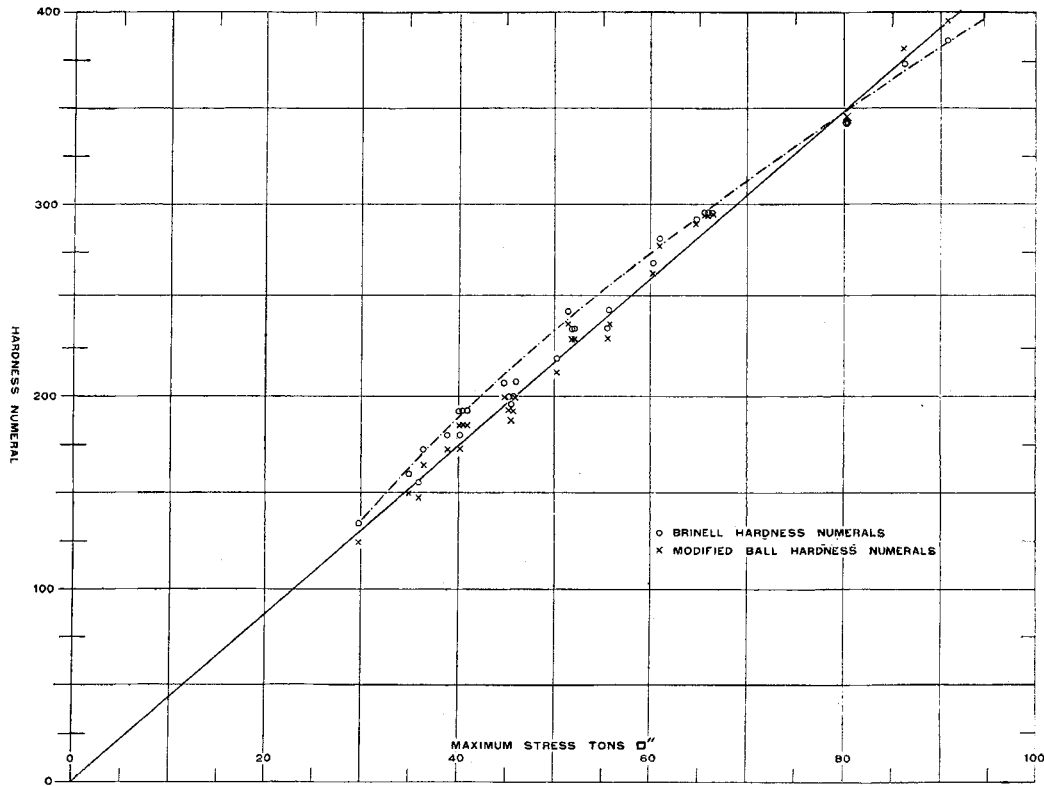
Numerous check tests proved that the size of the standard impression obtained from the calculated load in all cases varied within ± 1.0 per cent, thus proving the accuracy of the load curves within experimental limits.

The differences between ball and diamond figures in the lower ranges are also small, with the exception of manganese steel, but on the higher ranges the differences are large.

Now, it has been shown that the curve obtained in the same manner with a ball, that the values obtained with a diamond on the lower ranges, and that the loads to produce constant impressions, are all substantially correct; there is, therefore, reason to believe that the values obtained with the diamond in the higher ranges are also correct.

It follows, therefore, that on materials which are above 550 modified ball hardness (525 Brinell) the ball deforms to such an extent that the readings obtained are low and unreliable.

FIG. 12.—Correlation between Ball Test and Maximum Stress. Plain Carbon Steels.



APPENDIX V.

Correlation between Modified Ball Hardness Numerals and the Maximum Tensile Strength.

One of the most useful functions of the Brinell hardness numerals has been the indication of the approximate maximum tensile strength. An investigation has been carried out with a view to ascertaining the relationship between the ball hardness numerals and the maximum stress. So far plain carbon steels only have been dealt with, different grades being used.

The test-pieces were heat-treated in the form of bars 1 inch in diameter. They were turned to the British Standard Tensile Test C (0.564 inch diameter, 2 inches acting length), and the ball tests were taken on a surface about 0.28 inch from the axis. The maximum stresses obtained from these tests are plotted against the Brinell and modified ball numbers in Fig. 12.

It will be seen that the points given by the Brinell lie on a curve. The use of a simple factor is therefore incorrect. Those given by the modified ball hardness figures lie approximately on a single straight line which passes through the origin; a single factor of 0.23 therefore suffices. It will readily be seen that a far more accurate relationship is thus established