13TH JULY, 1899.

NOTES ON THE TESTING OF MATERIALS AT THE P. N. RUSSELL LABORATORY, WITH A SPECIAL REFERENCE TO NICKEL STEEL.

By W. H. WARREN.

Engineers depend mainly for the data which they possess on the physical properties of the materials used in construction upon the results which have been made in the various laboratories throughout the world. Nearly all of these are connected with Universities or Technical Colleges, and the investigations which are continually going on furnish the means of obtaining the most useful part of an engineer's education, besides giving results of scientific and practical value. The laboratory attached to the P. N. Russell School of Engineering, like others of its kind, has for its principal object, the training of engineers, but it has contributed also to our knowledge of materials, more especially in regard to our local requirements. It is proposed in the following paper to consider the methods employed in testing the physical properties of steel, with reference to its use in the construction of engines, boilers, bridges, rails, axles, tyres, and similar works. It is necessary to consider the following:—

1. The influence of the chemical composition on the physical properties of the material.

2. The strength—Tensile, compressive, transverse, torsional, and shearing.

3. The elastic limit, and coefficient of elasticity.

4. Ductility.

5. Resistance to shock, or suddenly applied stress.

6. The effect of repeated stresses applied in various ways.

7. Hardness and resistance to abraison.

8. The microscopic structure.

It is not proposed to discuss all these matters in detail, as it would render the paper far too long.

Chemical Composition.—It is well known that the chemical composition exercises a most important influence on the physical properties of the material, so much so that it is possible to determine approximately the tensile strength of a given steel of known chemical composition. Mr. Cunningham has given some results of Mr. Campbell's investigation as to the strengthening effect of the various components of steel,* and states that the strength of pure iron, as far as it can be determined, appears to be about 38,000 or 39,000lbs. per square inch, and the formula for acid steel is:—

Tensile strength = 38,600 + 121 carbon + 89 phosphorus + R.

For Basic Steel:—

Tensile strength = 37,430 + 95 carbon + 85 manganese + 105 phosphorus + R.

The carbon, manganese and phosphorus are expressed in units of 0.001 per cent., and the value of R. given in accordance with the conditions of rolling, and the thickness of the plates or pieces. The formulae were derived from experiments on structural steels, ranging from 0.02 to 0.35 per cent. of carbon, and probably do not apply to steels of harder quality or special alloys. The effect of nickel on the strength, ductility and elasticity of steel will be considered later.

*Proceedings American Society of Civil Engineers, Vol. XXIII,, No. 5.

The physical properties depend also on the mechanical treatment the steel has been subjected to in the process of manufacture from the ingot to the finished bar, rail, or girder, as the case may be. Again, the conditions under which it has been heated or cooled, i.e., its "heat treatment," are important, as it may cause the ultimate components of the mass to re-group themselves in new combinations. Many engineers specify the chemical composition of steel rails, but generally for other purposes and with few exceptions, it is considered more satisfactory to rely upon physical and mechanical tests, leaving the chemical composition to the steel manufacturer.

Physical Tests.—The strength, elastic limit, coefficient of elasticity, and the ductility are usually determined in the process of testing a specimen in tension, but the same properties may be determined by subjecting suitable pieces to compression, or beams to transverse stress.

In tension, compression, and transverse tests made on ductile materials there are three successive changes of state more or less clearly defined, which mark the limit of elasticity, the commencement of the plastic period, and the limit of cohesion or completion of the plastic period. The first change shows itself in tension tests, and in compression tests, when the pieces are sufficiently long, by the elongations or shortenings of the specimen ceasing to be proportional to the loads producing them, and by the disappearance of the deformation when the loads ar released. In transverse tests of beams the first change is marked in a similar manner by the deflections ceasing to be proportional to the loads producing them.

The second state is marked in tension, and in transverse tests by the commencement of the permanent elongations and deflections respectively, but in compression tests this change is shown by the swelling of the piece in the form of a barrel, termed by the French "refoulement." It is not necessarily, however, the limit of cohesion. In order that it may be developed in the test piece the length must not greatly exceed the diameter, or buckling will be produced.

The third change marking the limit of cohesion is shown in tension by the rupture of the specimen, in transverse tests of beams, also by rupture, unless the material is so soft and ductile, as in some kinds of mild steel, that the beams fail to support the load by bending pastically. In compression of short pieces the third change is shown by a decided swelling of the piece, although the load is perfectly supported.

It is very desirable that the results obtained in one laboratory should be comparable with those obtained in another, consequently, the form and dimensions of test pieces, the methods of procedure in testing, the precautions necessary to ensure accuracy, and all conditions which affect results should be uniform in every laboratory. To arrive at this state of affairs societies and conventions have been established in Europe and America, the most important of which is the International Society for the unification of the methods of testing the materials of construction, established by the late Professor Bauschinger in 1884.

In making a tensile test the test piece is divided into spaces ¼in. apart between the reference points, and fixed in the machine with holders having spherical bearing surfaces to ensure a uniform distribution of the stress over the sectional area of the test piece If the elastic limit and the coefficient of elasticity are required, a delicate extensometer, such as Marten's Mirror Apparatus, should be used, and the small elongations produced by equal increments of load carefully observed up to the point where they cease to be proportional, and beyond as far as the yield point. The coefficient of elasticity is the ratio of the stress to the strain, and may be expressed in terms of the ton or pound, and the inch, or in metric units. If the elastic properties of the material are not required to such a degree of accuracy, it will probably be sufficient to use a good form of autographic stress-strain apparatus.

It is evidently incorrect to express the total extension (which includes the local) as so much per cent., since up to the point where the maximum load is sustained, the elongations were proportional to the length of the specimen, and after that they are confined to the portion of the length, about which fracture ultimately takes place, and have nothing whatever to do with the original length. It is important to separate the general extension from the local, which may be done as follows: —Let the general extension per inch be denoted by X., and the local extension by Y. Then, if A. and B. denote the total extension on, say eight inches and four inches respectively, the latter being determined by measuring the length of the 16 spaces (originally $\frac{1}{4}$in.), including the fractured portion, then we have:—

$$A = Y \times 8\,x$$
$$B = Y \times 4\,x$$
$$\text{Therefore} \qquad Y = 2B - A$$

Or the local extension equals twice the total extension on 4 inches, less the total extension on 8 inches.

The general extension equals the difference between the total extension and the local extension.

The mechanical work, expressed in inch tons, which has been expended in stretching the bar up to the point where the maximum load was sustained, is clearly a measure of the quality of the material. Now this is equal to the area of the authographic diagram up to the ordinate, passing through M, and proportional to the product of the general extension and the tensile strength per square inch. This method of expressing the quality of the material was first proposed by Prof. Tetmayer, of Zurich, and it has been adopted by the Austrian Government and the American Society of Civil Engineers. It may be expressed in inch tons by multiplying the tensile strength per square inch by the general elongation per cent., and dividing by 100, thus:—

Let the tensile equal 30 tons per square inch, and the general elongation 18 per cent., then the co-efficient of quality becomes 5.4

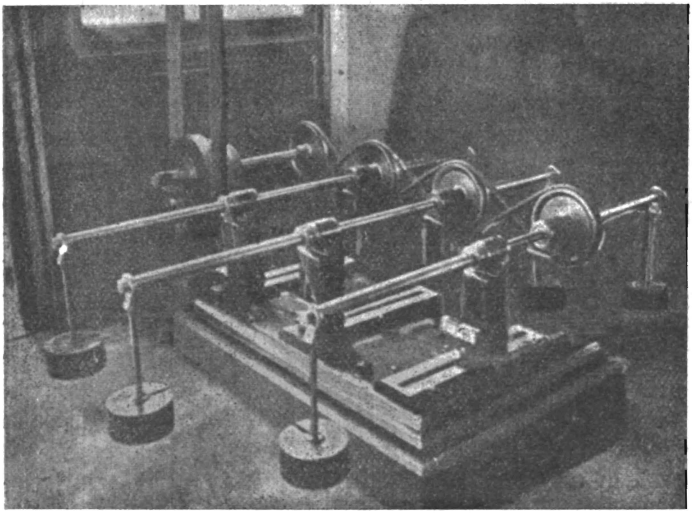
We may apply this principle in specifying the quality of steel in the following manner, thus:—

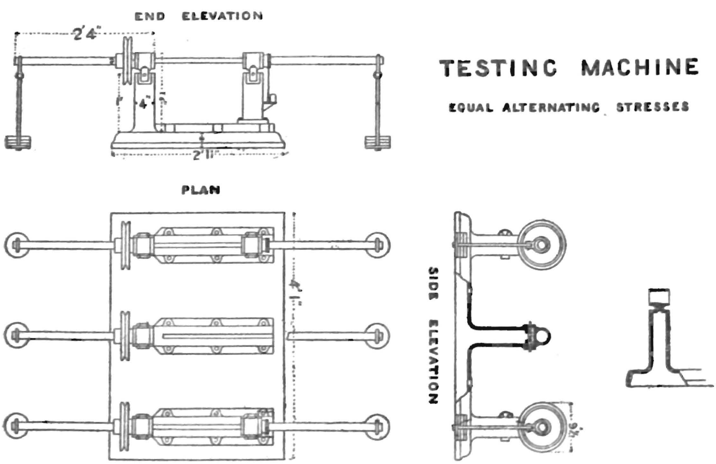
The tensile will not be less than 36 tons per square inch, and the product of the tensile strength and the elongation up to the point where the maximum load is sustained shall not be less than 540, i.e. general extension equals 540, divided by the tensile strength per square inch.

The ductility may be expressed by determining the area of the fracture, and expressing the reduction of area in per centage of original area. This however, is decidedly inferior to the method described in the foregoing. An excellent method of testing the ductility of steel is to subject strips of the material to bending and note the angle bent through before fracture; this should not be less than 180 when bent round a mandril, the diameter of which is twice the thickness of the strips. The strips should be 10 inches long by 1½ inches wide, planed on the edges and rounded slightly at the corners; they should moreover be divided into spaces ¼ inch apart and bent so that the divisions are on the outside. The elongations can then be measured on the outside over the most stretched 2½inch and expressed in per centage. Strips should be bent without treatment after preparation, and also after heating to a dull red, and cooling in water at 80 F.; the former test if satisfactory shows proper heat treatment in the process of manufacture; the latter, that the material is not too hard.

Resistance to shock.—The resistance to shock or suddenly applied load is best tested in an Impact machine, such as the one recently imported at the University, which is similar to the machine used by Professor Martens at Berlin, and designed to test specimens in an accurate manner. It admits of an extreme fall of 4.5 meters (about 15 feet), and of a weight of ram of 200 kilograms (440 lb.) also weights of 56 and 36 kilograms. The anvil weighs 1250 kilograms (2750 lb.), and will be set on a strong concrete foundation separate from the building. The machine is arranged for tension, compression and cross breaking tests, and there are special appliances for measuring the deformations. It is proposed to use the machine in testing materials such as axle steel, tyre steel, nickel steel, railway couplings, and generally for all cases in which material is subjected to suddenly applied loads.

The effect of repeated stresses.—These have been studies by Wohler, Bauschinger, Martens and others; and the results form the basis of the determination of the safe working stresses in structures. Experiments have been in progress for about a year at the P.N. Russell Laboratory on the same subject by the author with a special machine.




END ELEVATION
2'4"
4"
2'11"
PLAN
4'1"
TESTING MACHINE
EQUAL ALTERNATING STRESSES
SIDE ELEVATION

This machine was designed and constructed in the P. N. Russell Engineering School of the University, for the purpose of subjecting test specimens to equal alternating stresses, and thus determining the vibrating strength of the material. As will be seen from the diagram, three specimens are tested at the same time; and spare test pieces are kept in stock to replace those that are the first to fail, so that all the spindles may be maintained in continuous rotation. The three pedestals on one side of the base plate can be moved transversely, to allow of different lengths of test pieces being used. For exampe, it will be observed that in the illustration one of the test pieces is considerably shorter than the other two. The extreme lengths between the shoulders of the piece are 18in. and 3in. respectively. The specimen to be tested is screwed at each end into the overhanging spindles,, and these rotate in bearings supported on knife edges. In this way the bending moment is constant over the span from knife-edge to knife-edge, and the test piece in breaking will therefore select the plane of greatest weakness throughout its length. The machine has been used for determining the vibrating strength of materials, and the effect of alternating stress upon the position of the elastic limit.

Hardness and Resistance to Abrasion.—There are two senses in which the term hardness is used as applied to metals:—

a. Resistance to Indentation.

b. Resistance to abrasion or scratching.

In regard to the Resistance to Indentation, Col. T. J. Rodman (U.S.A.) proposed an indentation test by means of a pyramidal steel punch of special form attached to a falling weight, which has been standardized in France and depends upon the fact that the volume of material of a given quality displaced by the punch is equal to the energy of the blow "wh", divided by a constant "D" which constant is the work or energy necessary to displace (by deformation) a unit volume of that material. This constant is therefore characteristic of that material and may be taken as the index of hardness, or resistance to indentation. If L denotes the length of the indentation in millimetres, and W= weight of the ram in kilograms H=height of fall in millimetres the volume displaced by the Rodman punch is:—

$$\text{Vol} = 0{\cdot}0009413L^3 = V$$

$$\text{Then } V = \frac{Wh}{D} \text{ and } D = \frac{Wh}{V}$$

Professor Unwin, has proposed an indentation test specially suitable to ductile materials, in which the indenting tool is a straight knife edge; the test specimen indented is a short bar of square section. If "P" is the pressure per unit of width of knife edge in tons, "I" the depth of the indentation in inches, and "C" a constant for the metal tested then Unwin found that:—

$$CI = P^{1.2}$$

Professor Tetmayer has proposed to test the hardness of rails and the elastic limit by subjecting them to a bending test and noting the deflections thus:—

If "W" denotes the load in the centre which will just not produce a permanent set.

If "M" the moment of resistance of the rail with an extreme fibre stress equal to the elastic limit.

If "L" the span in inches.

$$\text{Then } W = 4\frac{M}{L}$$

After removal of the load the rail should spring back to its original shape.

The load to be afterwards increased up to about 32 tons per square inch, the deformations being observed and plotted or by means of auto-graphic apparatus for comparison as to hardness.—

$$W = 6\,7\,\frac{M}{L}$$

Resistance to Abrasion.—The most accurate method of determining the resistance to abrasion, or permanency of substance is by means of the Scratch test proposed by Mr. T. Turner, and recently standardised by Professor Martens. It consists of a pencil carrying a diamond point at its base, the load upon the pencil being made constant and the width of the scratch measured with a micrometer microscope.

Abrasion machines have been used, but they do not give results sufficiently uniform.

Microscopic Examination.—In connection with the failure of materials under repeated stresses with loads much less than would be necessary if gradually applied the term "Fatigue" has been used. This implies deterioration, but there is no proof whatever to support this theory, hence the term is not well chosen. Professor Johnson has proposed the term "Gradual Fracture of Metals" which appears to the author to more clearly represent what takes place. Mr. Thos. Andrews has proved by means of the microsope that there are thousands of incipient defects in the structure of steel, and it is probable that these gradually extend their weakening influence under repeated stresses in an irregular plane of cross section which ultimately become the plane of rupture.

These micro-flaws appear to be the initial cause of the weakness developed by repeated loadings. The micrographic analysis of iron and steel was inaugurated about thirty-six years ago by Dr. Sorby, and recently Professor I. O. Arnold, of Sheffield, and Professor Martens, of Berlin, have published most interesting and valuable information on the microscopic structure of steel. Professor Arnold's drawings are made by hand sketching the crystalline structure as revealed by the microscope, whereas Professor Martens' drawings are obtained by means of photography. The microscopic examination of steel is made upon highly polished sections of the metal, and has nothing to do with ordinary fractures.

The following investigation of the physical properties of nickel steel is given as a further example of testing, and as showing the physical properties of a comparatively new material which appears to the author to be especially adapted for a variety of purposes and which will in all probability be largely used in the future.

The tests were made from specimens selected by the author during a visit to the works of Fried. Krupp at Essen, Germany.

Three kinds of steel were tested which are denoted in the test sheets as follows:—

F—Mild,	containing	approximately	3	per cent nickel
T—Medium hard,	„	„	8	„
E—Non-rusting,	„	„	25	„

The tests made by the authors were somewhat restricted in consequence of the limited number of specimens available, but they are sufficient to bring out clearly the phsyical properties of the material.

6. Tensile Test.—These consisted in the first place in the determination of the elastic limit and coefficient of elasticity, the extensions being measured by Martens' mirror extensometer.* The test piece was afterwards divided between the reference points into spaces of one-quarter of an inch, and connected to the autographic apparatus and tested to destruction. The yield point recorded on the diagram is consequently higher than would have been the case if the test piece

*Obtained by adding the figures in the preceding two columns.

had not been previously strained in obtaining the true elastic limit. The results of these test are shown in Tables 1. to V., and in the summary Tables X. and XI.

The results of testing specimens cut from a railway axle made by Messrs. Vickers, of Sheffield, are also recorded, as showing the results of testing good steel of the ordinary kind, for the sake of comparing the results with those obtained from nickel steel.

7. Compressive Tests.—These consisted of the determination of the elastic limit and coefficient of elasticity as in the tensile tests, the compressions being observed with the Martens' mirror extensometer, the length of the specimens was ten inches, and diameter one inch; one set of readings was taken on a specimen two inches long. The compressive strength was determined by using cylinders one inch in diameter, and one and two inches long respectively. The compressive strength was taken as the yield point of the test piece. See Tables VI. to IX. and summary of results Table XII.

8. Torsion Tests.—These consisted of the determination of the value of f. in the equation—

$$f = \frac{T}{0{\cdot}196d^3}$$

and the measurement of the total angle of twist in degrees. See Table XIII.

9. Shearing Tests.—These consisted of the determination of the load necessary to shear the specimen on two planes, i.e. in double shear; the results are summarized in Table XIV.

10. Corrosion Tests.—To obtain an indication of the relative values of the nickel steels as regards their resistance to corrosion, specimen discs of various irons and steels were prepared as shown in the accompanying table. These were first weighed and placed in a large beaker containing about a gallon of a weak*

*One part by weight of strong sulphuric acid to one hundred parts of water.

solution of sulphuric acid, which was maintained at a temperature of from 170deg.—180deg. F. for twenty four hours. The discs were then removed, thoroughly cleaned, and re-weighed.

It is necessary to draw attention to the elastic limits obtained both in tension and compression, as the results may appear low when compared with similar results obtained from autographic apparatus. The large multiplication obtained by the Martens' mirror apparatus shows a deviation from the straight line much earlier than could be seen in any autographic diagram. Careful tests of Vicker's axle-steel made with Kennedy's extensometer gave an elastic limit of sixteen tons per square inch, whereas the Martens' apparatus gave 14.5 tons per square inch. Until a standard method for determining this point is agreed upon, it will always be difficult to compare the results obtained by experimenters using different extensometers.

The tables referred to will be found at the end of the volume.