CHAPTER II.

PHYSICAL PROPERTIES OF METALS.

Molecular Structure.—The physical aspects of metals are so pronounced as to render it difficult to abandon the old view that metals are sharply defined from other elements, and form a class by themselves. The term "metal" is in fact somewhat arbitrary. Zinc and bismuth, when they were first discovered, were considered to be semi-metals, and it was not until mercury was frozen by Braune in 1759 that it was recognised as a metal. Like all other elements, metals are composed of atoms grouped in molecules, and any force that alters the relations of the atoms in the molecules modifies the physical properties of the metals. Indeed, it would be easy to show that the physical constants of each metal vary with its degree of purity. The molecular grouping of metals is doubtless very varied, and little definite is known regarding the structural stability of most of them; but it may be assumed that it is not very great, as some metals split up into single atoms when they are volatilised, and most of them unite readily with chlorine and with oxygen.[1] The great interest which has of late been shown in the constitution and behaviour of metals and alloys has led to important results. The fact has been recognised that many laws of physical chemistry, hitherto considered mainly in relation to chemical compounds, are found to be applicable to metals and alloys. The result is that the barrier existing between metals and alloys and the non-metallic elements and compounds is being gradually removed. It is probable that in many pure metals, such as gold, silver, copper, and iron, the individual molecules are of simple atomic constitution, and that these fundamental molecules bear a uniform relationship to one another. Consequently, any mass, of which the fundamental molecules are the constituent particles, may practically be regarded as a single molecule. Two fundamental molecules must, however, be held to be capable of uniting to form complexes that have less power of cohering, and any circumstance tending to bring about the formation of such complexes would also tend to make the material less tough. This may account for the extraordinary alteration in the properties of many metals produced by very small quantities of incompatible foreign matters.[1]

Crystalline Structure of Metals.—This is a subject to which a considerable amount of attention has been directed in recent years. It is closely allied to and is, in fact, difficult to dissociate from the study of microstructure, which will be treated in a later chapter.

Much confusion arises from the failure to realise, at the outset, exactly what is meant by the crystalline structure. Before the microscope was adopted for the examination of metals, structure was generally understood to mean the appearance of a fractured surface which was referred to in such general terms as "fine-grained" or "coarse-grained." It is now more usual to compare structures as revealed by suitably etching a polished metallic surface. As regards the appearance of the fractured surface and the size of grain, mention should be made here of the classical work of Chernoff and of Brinell bearing on the changes in size of grain of steel under varying conditions of thermal treatment. The work of Osmond, Stead, Arnold, Howe, and others follows on similar lines, but with the aid of the microscope. Attention is drawn to the distinction between the grains of which a mass of metal is usually composed and the crystallites which compose each grain, the latter constituting the true crystalline structure. Further, it has been pointed out that in each grain the crystallites are arranged in a definite direction or orientation, and the growth of grains in soft steel as the outcome of annealing (a fact well known to steelworkers) has been considered[2] to be due to the orientation of the crystallites of adjacent grains becoming coincident. A wider knowledge of the conditions of growth of grains in other metals has resulted from the work of Ewing and Rosenhain.[3] It is therefore important to realise that changes occur in metals both in the size of the grains and in that of the crystallites composing them, as the result of changes of temperature which may be far below the melting-point of the metal. Frequently, the granular structure of a metal or alloy is either visible to the unaided eye or under low powers of the microscope, provided the surface be suitably polished and etched. The student should refer to *The Metallographist*, vols. i. to vi., 1898–1903; the *Journals of the Iron and Steel Institute*; and

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[1] Lothar Meyer, *Modern Theories of Chemistry*, English translation, 1888, p. 568.

[1] H. E. Armstrong, *Min. Proc Inst. C.E.*, vol. xciii. (1888), p. 112.

[2] Stead, *Journ. Iron and Steel Inst.*, 1898, ii. p. 137.

[3] *Proc. Roy. Soc.*, Bak. Lect., vol. cxciii. p. 353; also vol. cxcv. p. 279.

to the journals of similar institutions, for further particulars on this subject.

Density.—The density of a metal varies with the intimacy of the contact between the molecules. It is dependent, therefore, on the crystalline structure, and is influenced by the temperature of casting, by the rate of cooling, by the mechanical treatment, and by the purity of the metal. With the exception of bismuth, all pure metals are lighter when molten than when in the solid state. The density of a metal is augmented by wire-drawing, hammering, and any other physical method of treatment in which a compressing stress is employed. Mere traction, however, may diminish the density by tending to develop cavities in the metal. Pressure on all sides of a piece of metal increases its density. The density of standard gold, for example, by compression between dies is increased by 0·9, and cast discs of platinum, having a density of 21·21, may have the density increased to 21·46 by striking; whilst annealing such struck discs will again diminish their density. This shows that the compression is not permanent, and is solely due to the closing of pores. W. Spring[1] has even shown, by careful experiments on lead, tin, bismuth, antimony, cadmium, aluminium, and zinc, that a pressure of 20,000 atmospheres continued for many days is sufficient to effect the obliteration of all the pores. The specific gravities of the various metals are given in the table on p. 67. Lithium is the lightest metal, and osmium the heaviest, the specific gravity of the former being 0·54 and that of the latter 22·48.

So early as 1845, Joule[2] recognised the importance of determining the specific gravity of melted metals, seeing that "this condition would completely obviate the influence of cohesion, or that of any particular molecular arrangement." His method, which was essentially that afterwards adopted by Mallet[3] and by the author,[4] may be described as follows:—It consists in filling with molten metal a vessel, the capacity of which may be calculated for the particular temperature at which the molten metal is introduced. The weight of the metal when cold, divided by the weight of water which the expanded vessel is capable of holding, gives the fluid density of the molten metal. Subsequently the author[5] and T. Wrightson determined the fluid density of several metals by means of the oncosimeter as given below.

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[1] *Bull. Soc. Chim. Paris*, vol. xxxix. (1883), p. 515; and Gray, *Proc. Roy. Soc.*, vol. liv. (1893), p. 28.

[2] Collected Papers, published by the Physical Society, vol. ii. p. 136.

[3] *Proc. Roy. Soc.*, vol. xxii. (1873), p. 366; and vol. xxiii. (1874), p. 209.

[4] *Ibid.*, vol. xxiii. (1874), p. 481.

[5] *Phil. Mag.*, vol. xi. (1881), p. 295; vol. xiii. (1882), p. 360.

	Specific Gravity of Solid.	Fluid Density.		Percentage of Change in Volume from Cold Solid to Liquid.	
		By Mallet's Method.	By Oncosimeter.		
Bismuth . . .	9·82	10·039	10·055	Decrease of vol.	2·30
Copper . . .	8·80	...	8·217	Increase of vol.	7·10
Lead . . .	11·40	10·650	10·370	,, ,,	9·93
Tin . . .	7·50	6·974	7·025	,, ,,	6·76
Zinc . . .	7·20	6·550	6·480	,, ,,	11·10
Silver . . .	10·57	9·460	9·510	,, ,,	11·20

The question of the fluid densities has also been investigated by Nies and Winkelmann,[1] who have adopted another method, determining the liquid density by observing the weights of blocks which just sink and just float. With regard to bismuth, C. Lüdeking[2] finds that this metal, like water, attains a maximum density just before becoming solid, the expansion at the moment of solidification being about 3 per cent. of the volume.

In 1895, Keep[3] described his apparatus for measuring the volume of a cast bar of metal or alloy, from the moment it begins to solidify until it reaches the atmospheric temperature, with which he studied the contraction of many solidifying metals and alloys. Prof. Turner[4] of Birmingham improved on Keep's apparatus, and also used a pyrometer for measuring the temperatures during solidification, contraction, and cooling.

From a large number of determinations, he found that the following four different types of curves could be obtained on plotting time and shrinkage:—

Type 1.—The contraction curve is uniform and there is no arrest in the decrease of volume as the metal cools. Copper, aluminium, antimony, lead, tin, and zinc yield curves of this type.

Type 2.—There is one point of retardation of the contraction, which may or may not lead to an actual expansion. White-iron, high carbon steel, and the copper-zinc alloys (many of which expand on solidification) belong to this class.

Type 3.—Two arrests in the rate of contraction are seen in this class, to which belongs non-phosphoric grey iron.

Type 4.—Three distinct arrests occur in this class, a characteristic curve being given by a very grey phosphoric iron.

From the curves given, Prof. Turner shows that during solidification there is no actual expansion with white iron, but with

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[1] *Stizungsber. der Acad. der Wissen. zu München*, 1881, p. 63.

[2] *Ann. Phys. Chem.*, vol. xxxiv. (1888), p. 21.

[3] *Journ. Iron and Steel Inst.*, 1895, ii. p. 227.

[4] *Journ. Iron and Steel Inst.*, 1906, i. p. 48.

grey irons there are two expansions, and with phosphoric grey irons there are three.

Fracture.—Fracture has long been used as a practical guide to the fitness of a metal, as in the refining of copper, the manufacture of steel, and in "grading" pig-iron. The influence of heat on the fracture of steel, although long recognised, was first dealt with systematically by Chernoff, and later and more fully by Brinell.[1] The appearance of the fractured surface of a metal depends partly on the nature of the metal and partly on the manner in which solidification occurred. Sudden cooling to a great extent prevents the formation of crystals, whilst slow cooling facilitates their development. Long-continued hammering and frequent vibrations will produce the latter result. Any condition that affects either the cohesion or the crystalline structure of a metal affects its fracture. Thus, lead broken when hot has a columnar structure; not so when broken cold.

The relation between the fracture and the internal structure of steels has received much attention; Seaton and Jude[2] examined the fractures produced by impact tests, and came to the conclusion that the line of fracture passed mostly through the ferrite portions, partly through the ferrite and pearlite junctions, and partly through the pearlite. Bannister[3] has shown that irregular and laminated fractures are frequently associated with "ghosts" or slag lines; and Rosenhain[4] has shown that in tensile fractures the break runs through the ferrite and pearlite almost indifferently, but in impact tests the break occurs in the ferrite for the most part, while bending fractures are of an intermediate character.

The ordinary mineralogical terms regarding colour and fracture are used in relation to metals. Practice, however, can alone enable the student accurately to describe these appearances.

Malleability.—This is the property of permanently extending in all directions, without rupture, by pressure produced by slow stress or by impact. Metals showing marked crystallisation, such as antimony and bismuth, are not malleable, and any circumstance that tends to produce crystallisation must affect the malleability. Thus in nearly all metals the malleability becomes impaired when they are subjected to rolling or long-continued hammering; but this property may be regained by annealing, which consists in raising the metal to a high temperature and allowing it to cool, either rapidly or slowly, usually the latter. At different temperatures metals behave in different ways; some are malleable when at a red heat, but not so when cold. These are defined as being *cold-short*.

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[1] *Journ. Iron and Steel Inst.* (1886), p. 365; Howe's *Metallurgy of Steel*, p. 170; *Stahl und Eisen* (1885).

[2] *Proc. Inst. Mech. Eng.*, 1904, iv. p. 1135; *Engineer*, vol. xcviii. pp. 517 and 528, Nov. 18, 1904.

[3] *Journ. Iron and Steel Inst.*, 1906, i. p. 161.

[4] *Journ. Iron and Steel Inst.*, 1906, ii. p. 189.

Others are malleable when cold, but not when at a red heat. These are described as being *red-short*. Some metals are malleable at all temperatures, others are not malleable at all. Zinc is brittle when cold and when hot, but at a temperature of 150° it is malleable. The malleability of a metal depends largely upon its purity. Relative malleability is shown by the degree of thinness of the sheets producible by beating or rolling the metals without annealing.

Ductility is the property that enables metals to be drawn into wire. It generally decreases with an increase in the temperature of the wire at the time of drawing, but there is no regular ratio between the two. Iron is less ductile at 100°, and more ductile at 200° than it is at 0°. Malleable metals are also ductile, but they do not possess the two properties in the same order. Arranged according to their malleability, the more important metals follow this order:—(1) Gold; (2) Silver; (3) Copper; (4) Tin; (5) Platinum; (6) Lead; (7) Zinc; (8) Iron; (9) Nickel. The order of ductility, on the other hand, is (1) Gold; (2) Silver; (3) Platinum; (4) Iron; (5) Nickel; (6) Copper; (7) Zinc; (8) Tin; (9) Lead. The rate at which the traction is applied has great influence in testing malleability and ductility.

Tenacity is the property possessed by metals, in varying degrees, of resisting the separation of their molecules by the action of a tensile stress.

Toughness is the property of resisting the separation of the molecules after the limit of elasticity has been passed.

Hardness is the resistance offered by the molecules of a substance to their separation by the penetrating action of another substance or by abrasion. Great differences are observable between the hardness of the different metals, and many methods have been devised for its determination.

The results of the experiments of Bottone[1] gave valuable information. In these determinations the time necessary to produce a cut of definite depth when pressed against an iron disc revolving in a lathe, at definite speed, was taken as a measure of the hardness of the material. Prof. Turner[2] also investigated the hardness of metals and devised a sclerometer for the purpose of determining hardness.

This instrument has been modified by Keep, and consists of a diamond placed at the end of a well-balanced arm. By sliding a set of weights along the beam, a point is reached when the diamond makes a standard scratch. From the weights used and the position on the arm the relative hardness can be calculated. Brinell's[3] method of testing hardness is now largely used, and consists in producing an indentation in the material under ex-

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[1] *Chemical News*, 1873, vol. xxvii. p. 215.

[2] *Proc. Birmingham Phil. Soc.*, vol. v., 1886, part ii.

[3] *Hallfasthetsprof*, by Wahlberg, Stockholm, 1901. *Journ. Iron and Steel Inst.*, 1901, i. p. 243; 1901, ii. p. 234.

amination by forcing into it a hardened steel ball. The maximum pressure applied, divided by the spherical area of the concavity (deduced from its diameter), gives as a quotient a number called the hardness number. The figures give a comparative determination of hardness only, and the following are the hardness numbers obtained for some metals and alloys:—

Rolled copper	74	Phosphor bronze	130
Silver	59	Bell metal	124
Antimony	55	Brass	63
Gold	45	Phosphor tin	19·7
Zinc	46	Rose metal	6·9
Aluminium	38	Mild steel 0·1 C.	100
Tin	14·5	Medium steel 0·45 C.	200
Lead	5·7	High carbon steel 1·25 C.	300

A description of the machine used for obtaining the hardness number will be found under Testing Machines, page 33.

Prof. Unwin[1] also devised a method for testing hardness, similar in principle to Brinell's, in which a knife-edge was used for producing the indentation, instead of a ball, and the hardness number calculated from the load applied and depth of indentation produced.

Boynton[2] has recently used Jaggar's microsclerometer for the determination of the hardness of the different constituents of iron and steel. The principle of this instrument is as follows:—A diamond point of constant dimensions is rotated on the specimen at uniform rate, under uniform weight, to a uniform depth. The number of rotations necessary varies as the resistance of the material to abrasion by diamond. As a result of these determinations, the following figures were obtained:—

Constituent.	Present in	Average Hardness.	Ratio.
Ferrite	Electrolytic iron	460	1
,,	,, ,, (quenched)	990	2·15
,,	Commercial wrought irons	686 to 1643	1·5 to 3·6
Pearlite	Series 0·13 to 1·52 per cent. carbon	842 to 4711	1·8 to 10·3
,,	Series 0·35 to 0·86 per cent. carbon	1745 to 2150	3·8 to 4·2
Sorbite	Steels 0·48 and 0·58 per cent. carbon	2400 to 24,650	5·2 to 53·6
Troostite	Steel 0·58 per cent. carbon	40,560	88·2
Martensite	Series 0·2 to 1·52 per cent. carbon	17,896 to 120,330	38·9 to 261·6
Austenite	White cast iron 3·24 per cent. carbon	47,590	103·4
Cementite	White cast iron 3·24 per cent. carbon	125,480	272·8

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[1] *Proc. Inst. Civil Engineers*, vol. cxxix., 1897.
[2] *Journ. Iron and Steel Inst.*, 1906, ii. p. 287.

Brittleness is the sudden interruption of molecular cohesion when the substance is subjected to the action of some extraneous force, such as a blow or a change of temperature. It is influenced by two distinct sets of conditions: one of these is the nature of the metal itself, such as chemical composition, structure, admixture with foreign matter, such as slag, blowholes filled with gas, etc.; and the other, the external conditions to which the metal is subjected, such as degree of stress, rate at which the stress is applied, shape of the test piece under examination, and temperature. Many cases of brittleness occur for which, at present, there is but imperfect explanation. Drop tests and falling weight tests are often the means of detecting material which, though satisfactorily fulfilling other conditions, yet is quite brittle under sudden shock. Fréminville[1] has studied the influence of vibration on the brittleness of bars of metal, and there has been much work done on brittleness in iron and steel; Stead[2] describes how soft steel may be rendered brittle by annealing; Law[3] shows that brittleness in steel sheets may result from high sulphur and phosphorus in the original ingots; and Charpy,[4] who has studied the effect of temperature on brittleness, states that in mild steels the minimum brittleness lies between 0° and 150° C., and the maximum brittleness between 250° and 500° C.

Elasticity, Extensibility, and Strength of Metals.—At first sight it might seem that testing the mechanical properties of metals is more within the province of the engineer than that of the metallurgist. The latter has, however, not only to extract metals from their ores, but also to fit them for use. He must therefore know what mechanical properties[5] are possessed by the more important metals and alloys, and be able to submit them to experimental tests, instead of merely trusting to statements recorded by others.

Elasticity is the power a body possesses of resuming its original form after the removal of an external force which has produced a change in that form. The point at which the elasticity and the applied stress exactly counterbalance each other is termed the **limit of elasticity**. If the applied stress were then removed, the material acted upon would resume its original form. If, however, the stress were increased, the change in form would become permanent, and **permanent set** would be produced. When considering, however, the stresses which a structure is

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[1] *Revue de Métallurgie*, vol. iii. p. 61.
[2] *Journ. Iron and Steel Inst.*, 1898, ii. p. 137.
[3] *Journ. Iron and Steel Inst.*, 1906, i. p. 134.
[4] *Bulletin de la Société des Ingénieurs Civils*, 1906, p. 562.
[5] The more important works dealing with this subject are:—Kennedy, *Proc. Inst. C.E.*, vol. lxxxviii. (1887), p. 1; Unwin, *Testing of Materials of Construction*, 1889, Longmans; Lebasteur, *Les Métaux à l'Exposition Universelle*, 1878; J. Résal, *Constructions Métalliques: Elasticité et résistance des matériaux*, 1892; Martens, *Handbook of Testing Materials*, translated by Heming.

expected to bear without suffering "molecular fatigue," something considerably below the elastic limit is taken.

A very convenient term which expresses the condition of metals under stresses, when confined within the elastic limit, is that of "limit of proportionality," which has been given by French and German investigators to the point at which the strain ceases to be strictly proportional to the stress. Within the limit of elasticity, a uniform rod of metal lengthens or shortens equally under equal additions of stress. If this were the case beyond that limit, it is obvious that there would be some stress that would stretch the bar to twice its original length, or shorten it to zero. This stress, expressed in lbs. or tons for a bar of 1 inch square cross section, is termed the **modulus of elasticity**. As an illustration, let it be supposed that a bar of steel 1 inch square and 10 inches long is stretched by a force of 2240 lbs., and to have elongated under the action of this stress 0·00075 inch, the modulus of elasticity of this bar would be the force that would be required to elongate it by 10 inches, and this would be

$$0{\cdot}00075 : 10 :: 2240 : x,$$

$x = 29{\cdot}9 \times 10^6$ lbs. per square inch. Hence the modulus of elasticity is a stress that bears the same proportion to the original length of a uniform bar as the stress that will produce any given amount of strain bears to the length of this strain, the term **stress** meaning an equilibrating application of force to a body, and the term **strain** meaning any definite alteration of form or dimensions sustained by that body. The modulus of elasticity may thus be defined as being the number obtained by dividing the number expressing the stress by that expressing the strain that it produced. Unwin expresses this as follows:—

Let p be the stress reckoned on unit of area, and λ the extension or compression reckoned per unit of length.

Then, by Hooke's law, $\frac{p}{\lambda} = \mathrm{E}$, a constant which is termed the coefficient of direct elasticity, or Young's modulus. It has the same value for tension and compression.

Thus, to take the above case of a sample of mild steel:—
Load applied, 2240 lbs. per square inch.
Extension produced, 0·00075 inch.

$$\mathrm{E} = \frac{2240}{0{\cdot}000075} = 29{\cdot}9 \times 10^6 \text{ lbs. per square inch.}$$

Prof. Kennedy finds the **specific extension** to be a quantity most useful in works. This is the extension in thousandths of an inch on a length of 10 inches under a stress of 1000 lbs. per square inch. Its reciprocal, multiplied by 10 millions, is the modulus of elasticity in lbs. per square inch.

In measuring the strength of metals, it is necessary to determine—

1. The greatest **stress** the metal can sustain within the limit of elasticity.
2. The **strain** within the limit of elasticity.
3. The total extent of the **strain**, or alteration of form before rupture takes place.
4. The ultimate **tensile strength** or maximum stress the material can sustain without rupture.
5. The **reduction of area** at the point of fracture.

The limit of elasticity and the breaking stress are the points which have usually to be determined, and these alone will be considered here. For information as to torsional and compression tests, the student is referred to the works of Unwin and Kennedy.

In testing a piece of metal, the first point to be determined is the limit of elasticity. When a metal, such as iron or steel, is submitted to stress by pulling its ends in opposite directions, it stretches uniformly throughout its length. There is, however, in such a solid a limit in the application of the stress up to which the metal, if released, will return to its normal length. This point is the limit of elasticity. It is, however, certain that a very small application of load produces permanent deformation, so that the determination of the exact limit of elasticity will depend upon the delicacy of the instruments used for its measurement. It is safe to consider the limit of elasticity to be the point at which the stresses and strains cease to be exactly proportional. If the strains are plotted as abscissæ and the stresses as ordinates, points will be obtained on a curve giving the relation of stress and strain for the whole test. Up to the limit of elasticity, this curve is almost a straight line; but when that point is passed, the molecular arrangement of the metal breaks down, and, as Prof. Unwin expresses it, probably the breaking-down point (which is not to be confounded with the limit of elasticity[1]) is a kind of physical record of the condition of constraint in the bar at the moment of rolling or hammering. Fig. 1 is a curve obtained by an automatic recorder, showing the limit of elasticity, yield point, and breaking-down point of a specimen of open-hearth mild steel. It has been suggested by Osmond that in the case of iron or steel, any stress which produces a permanent deformation is attended by a rearrangement of the molecules of the metal. In support of this view, it may be mentioned that Carus Wilson[2] has examined this point of the stress-strain curve with much care, and shows that the peculiar bending of the

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[1] See also Gautier, "Discussion on Testing Machine," *Journ. Iron and Steel Inst.*, vol. ii. (1888), p. 31.

[2] *Phil. Mag.*, vol. xxix. (1890), p. 200. See also the Sixth Report to the Alloys Committee, *Inst. Mech. Eng.*, 1904, p. 14.

curve indicates the condition of strain in a steel bar, since by gradually increased stress the steel may be converted from an elastic solid to a viscous fluid. He compares such curves (I to IV) fig. 2 for steel of different hardness with the stress-strain curves of a gas at different temperatures, there being strong probability that in both cases the apparent discontinuity, at A F, B E, and C D, is really a double inflection due to a change taking place piecemeal throughout the mass. Fig. 2 shows Carus Wilson's curve for the yield point of steel, and fig. 3 shows Andrew's curve exhibiting the passage of carbonic anhydride from the gaseous to the liquid state. Probably the increase in the breaking stress and diminution in the elongation, which has been found to result from the application of long-continued stress to steel, is the result of the molecular change in the metal. It is also known that the prolonged application of a load to steel raises the elastic strength. This appears to afford additional evidence of molecular change. If the load is slowly applied, the stress-strain curve will be flatter than if it is applied rapidly.

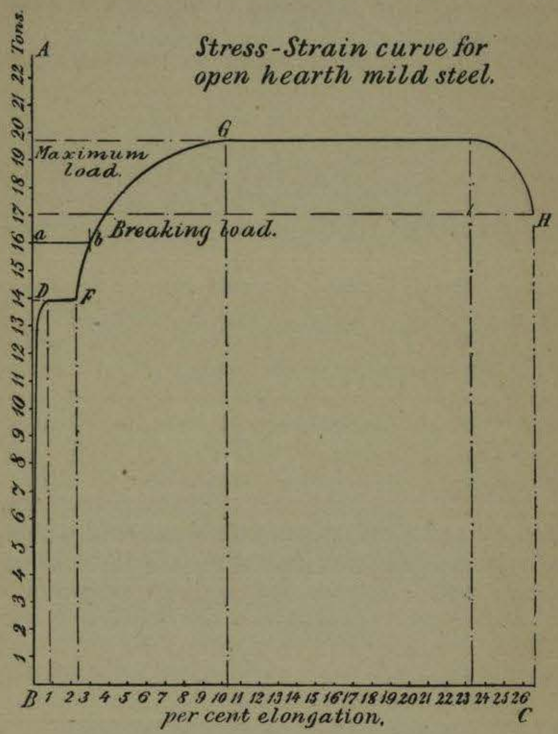

FIG. 1.—Elastic limit, 13·5 tons; D, yield point; F to G. curve of extension between yield point and maximum load; G, maximum load, 19·86 tons; H, breaking load, 17 tons. By dropping perpendiculars from any point in the curve, as at D, F, G, or H, to cut the base line, we get the percentage elongation for any particular load. Thus, at D it is rather under 1 per cent., at F just under 2·5 per cent., at G 10·25 per cent., and at H 26·65 per cent. Similarly, by drawing lines from any point in the curve parallel to the base line to cut the perpendicular load line, we can get the load on the specimen for any particular point in the curve.

Colonel Maitland[1] has conclusively shown that in the case of the unhardened steel used for the manufacture of guns, the ultimate elongation is considerably increased by the rapid application of the load. The steel used showed a tenacity of 26 tons and an elongation of 27 per cent. on the length of 2 inches by the ordinary test, but when screwed into blocks, made to fall vertically in a slide, and arranged so that after a certain height of fall the top block was arrested by stops, and the specimen broken by the momentum of the lower block, the elongation increased to 47 per cent. On further increasing the rapidity of load by screwing the specimen into plugs fitting a strong tube, and exploding gun-cotton or gunpowder between

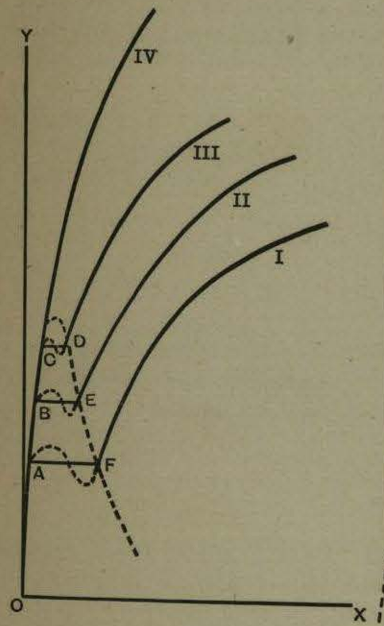

FIG. 2.

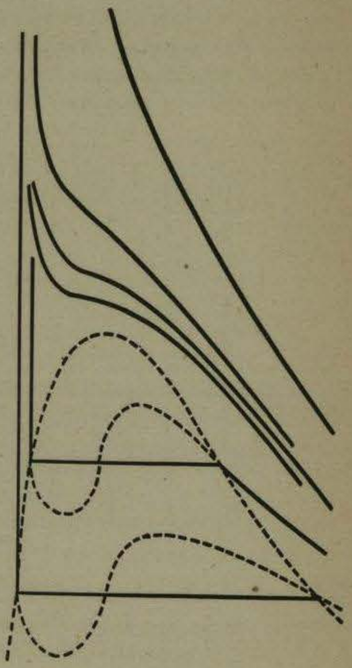

FIG. 3.

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[1] *Min. Proc. Inst. C.E.*, vol. lxxxix. p. 120.

the plugs, thus driving them out in opposite directions, an elongation of 62 per cent. was obtained.

Effect of High Temperatures on the Properties of Metals.

It is important to ascertain in what way the mechanical properties of metals are modified when they are submitted to tests while hot. André le Chatelier[1] has published some experiments in this direction in connection with a research on the influence of temperature on the mechanical properties of iron and steel. His results as regards a pure variety of ingot iron or mild steel containing 0·05 per cent. of carbon are given in the curves (fig. 4).

The effect of heat is to produce two modifications in the mechanical properties of iron and steel; there being a very noticeable reduction in elongation at a temperature of about 80°, and an increase in the tensile strength at about 240°. These changes depend both on the temperature and on the speed with which the load is applied. The fragility of iron to shock is at its maximum at 300°, but it also possesses at this temperature a maximum resistance both to longitudinal stress and to extension if the load is slowly applied.

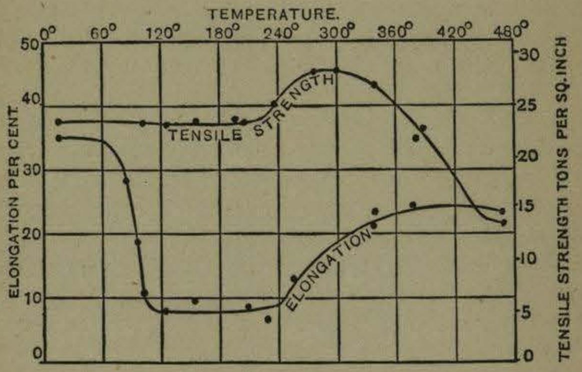

FIG. 4.

These results have been substantially confirmed by Ledebur[2] and others, but in many cases there is shown a slight decrease in tensile strength from - 80° C. to a temperature of 60° C. to 100° C., after which a gradual increase is observed until about 320° C., when there is a gradual falling off again.

In the case of most ordinary metals, the tensile strength gradually diminishes as the temperature is raised, as is illustrated by the following table from the work of Baudrimont.[3]

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[1] *Comptes Rendus*, vol. cix. (1889), p. 58.

[2] *Zeit. des Vereines deutscher Ingenieure.* vol. xl. p. 565.

[3] *Annales de Chimie et de Physique*, 1850.

TENSILE STRENGTH IN POUNDS PER SQUARE INCH.

	At 0° C.	At 100° C.	At 200° C.
Gold	26,208	21,662	18,332
Platinum . . .	32,144	27,440	24,528
Copper	35,728	31,136	26,000
Silver	40,320	33,040	26,432
Palladium . . .	51,856	46,144	38,528

Effect of Low Temperatures on the Properties of Metals.

The effect of low temperatures on the mechanical properties of metals has received much attention of late years, one of the first investigators being Andrews, who published a paper in 1886 on the "Effect of Temperature on the Strength of Railway Axles."[1] The lowest temperature used in these experiments, however, was only - 45° C. As a general rule, the effect of very low temperatures on the common metals is to increase the tenacity, as measured by the breaking load, and to increase the hardness, as measured by the Brinell test.

Hadfield's experiments[2] showed that pure iron, soft and ductile at ordinary temperatures, became brittle, lost its ductility, and increased in hardness number from 88 to 263 on the Brinell scale, at liquid air temperatures, but on again reaching normal temperatures, became as soft and ductile as before.

Metallic nickel showed remarkable results when tested in liquid air, the tenacity increasing from 29 to 46 tons, the ductility from 43 to 51 per cent., and the hardness number from 100 to 150, and this fact probably explains why, in iron-nickel and iron-nickel-manganese alloys, the presence of nickel, provided there is a low percentage of carbon, prevents low temperatures, such as - 150° C. to - 200° C., injuriously affecting the properties of the alloy. These alloys are dealt with on page 108. Metallic copper resembles nickel, the tenacity being increased, though not to the same extent, the ductility remaining the same and the hardness increasing from 77 to 90. Metallic manganese differs entirely from nickel and copper, being comparatively brittle at low temperatures. Aluminium shows increases in tenacity from 8 to 15 tons and ductility from 7 to 27 per cent. when tested in liquid air. Lastly, the effect of low temperatures on the ductility of lead and tin is most interesting, for although at ordinary temperatures they elongate about the same amount before breaking, tin breaks at - 182° C. without any extension,

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[1] *Proc. Inst. Civil Eng.*, vol. lxxxvii., 1886-7, p. 340.

[2] *Journ. Iron and Steel Inst.*, 1905, I. p. 147.

while lead under similar conditions shows no change, stretching as much at − 182° C. as at 15° C.

The following table gives the ultimate strength of a number of metals at ordinary temperatures:—

	Ultimate Strength. Lbs. per sq. in.		Ultimate Strength. Lbs per sq. in.
Copper, cast	19,000	Lead, sheet	3,200
,, annealed	29,100	Tin	3,400
,, hard drawn	40,000	Gold, pure, cast	15,680
Iron, cast, weak	13,400	,, drawn	38,000
,, average	16,500	Silver, drawn	40,000
,, strong	27,300	Platinum	35,000
Iron, wrought, plates	49,000	,, wire	44,000
,, ,, bars	55,000	Aluminium, cast	10,976
Steel, mild	50,000	,, bars	16,128
,, medium	88,000	,, drawn	19,488
,, high carbon	132,000	,, plates	20,160

The influence of foreign elements on the tensile strength of metals is dealt with in Chapter III.

Testing Machines.—The elasticity and strength of metals are determined by the aid of testing machines, the more important of which are based on Kirkaldy's principle of applying the load by water pressure and measuring it by dead weight. In small machines, the hydraulic ram may be replaced by a screw and gearing. Figs. 5 to 8, copied from Prof. Kennedy's admirable paper on engineering laboratories,[1] illustrate the principle of several types of testing machine, without showing the details of their construction. In the Werder machine (fig. 5), which has been largely used on the Continent, the test piece, *a*, is held at one end in the frame of the machine, *e*, and at the other pulled by means of the ram, *b*, from the short arm, c_1, of a knee lever, to the long arm of which hangs a scale-pan, *d*, on which the pressure is balanced. The ratio of c_2 to c_1 is 500 : 10. The central fulcrum of the lever rests on the end of the ram, *b*, so that the whole measuring apparatus moves along as the piece extends and the ram moves out, the arm, c_2, being always kept horizontal by the aid of a spirit-level.

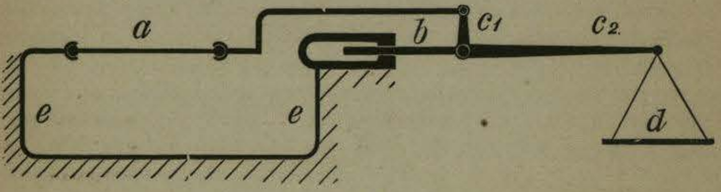

FIG. 5.

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[1] *Min. Proc. Inst. C.E.*, vol. lxxxviii., 1887, p. 1.

Wicksteed's machine[1] (fig. 6) is a vertical one with a single lever, $c_1\,c_2$, placed horizontally on the top. A movable poise, *m*, measures the load, a downward pressure being applied to the ram, *b*, by a screw or pump. The ratio of c_2 to c_1 is 50 : 1. In a 100-ton machine, the weight, *m*, is 1 ton, so that it balances a pull of 50 tons when at the end of c_2. To carry the load on to 100 tons, *m* is run back beyond the fulcrum, and a second weight of 1 ton is hung to the end of c_2. The poise weighs 1 ton, and is moved along the lever by a screw worked by power. Each 3 inches of movement of the poise adds 1 ton to the load on the test piece, whilst a vernier attached to the poise may be read, on a scale affixed to the lever, to one-hundredth of a ton.

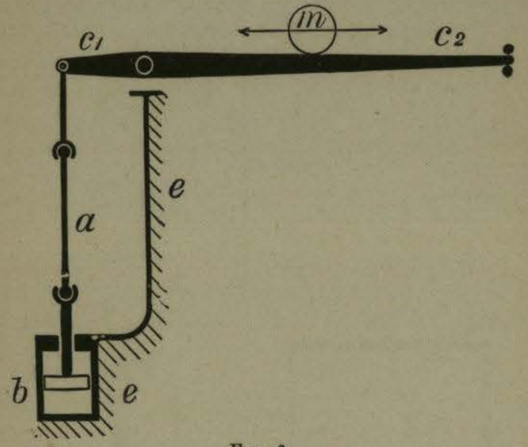

FIG. 6.

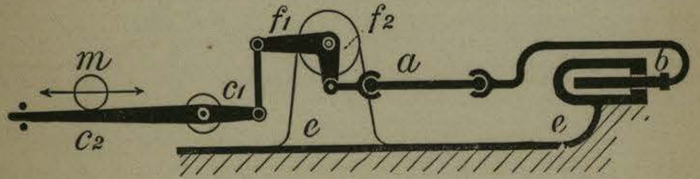

FIG. 7.

Greenwood's machine (fig. 7) was formerly largely used in this country. It is a horizontal machine with two levers, a knee lever, $f_2 f_1$ (5 : 1), and a steelyard, $c_2\,c_1$ (20 : 1), the total leverage being 100 : 1. The load is applied by the ram, *b*, and measured by the position of the poise, *m*, on the steelyard.

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[1] *Inst. Mech. Eng. Proc.*, 1882, p. 384.

Gollner's machine (fig. 8) is a double lever vertical machine, working up to 20 tons. Both screw and ram may be provided with means for changing at once from one to the other.

A general sectional elevation of a modern Wicksteed machine, the principles of which have been described on page 27, is shown in fig. 9. This machine was built a few years ago for the Bradford Technical College by Messrs Buckton, and described by Mr G. F. Charnock in *Engineering*, from which article the drawing and description are taken. The machine is worked from an accumulator, G, and the ram, H, 4½ inches in diameter, is loaded to a pressure of 3000 lbs. per square inch, from a crosshead I, from which is suspended a load of about 24 tons of cast-iron slabs I¹. The accumulator is supplied by an automatic pump L.

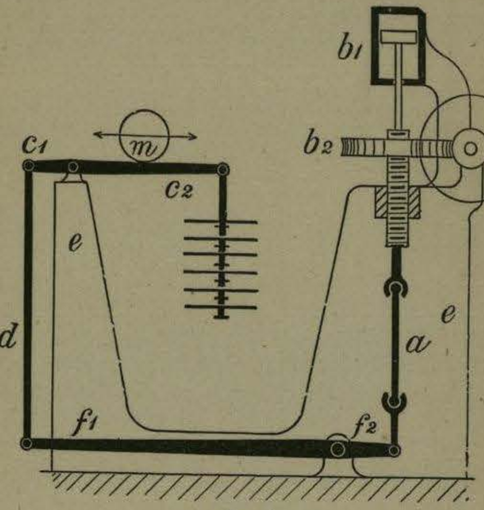

FIG. 8.

The machine itself consists of a main standard, Q, a heavy box casting firmly secured to a massive stone foundation. The hydraulic straining cylinder, R, of 10 inches diameter and 12 inches stroke, is securely fixed in an inverted position to the base of the standard. The ram thus acts downwards, its crosshead, S, being connected by the two strong side screws, T, to the upper crosshead, U, which is guided by V slides on the face of the main standard, and in which is formed (1) the gripping-box for the lower end of a tension specimen Y, (2) a face for the upper end of a compression specimen when used for these tests; or (3) a pressure foot to apply the load at the centre of a beam specimen, when the machine is used for bending tests. The screws, T, are operated by worm gearing, worked by the handle, Z, and enable the adjustment to any length of either tension or compression specimen up to 6 feet to be effected. The balance-weight, *a*, carried upon the end of spring levers, causes the return stroke of the ram to be made after the conclusion of a test. The valve, *b*, admitting pressure from the accumulator, and the exhaust valve, *c*, for return to tank, are of the screw pattern worked by hand-wheels, and are easily adjustable to suit any speed of testing desired.

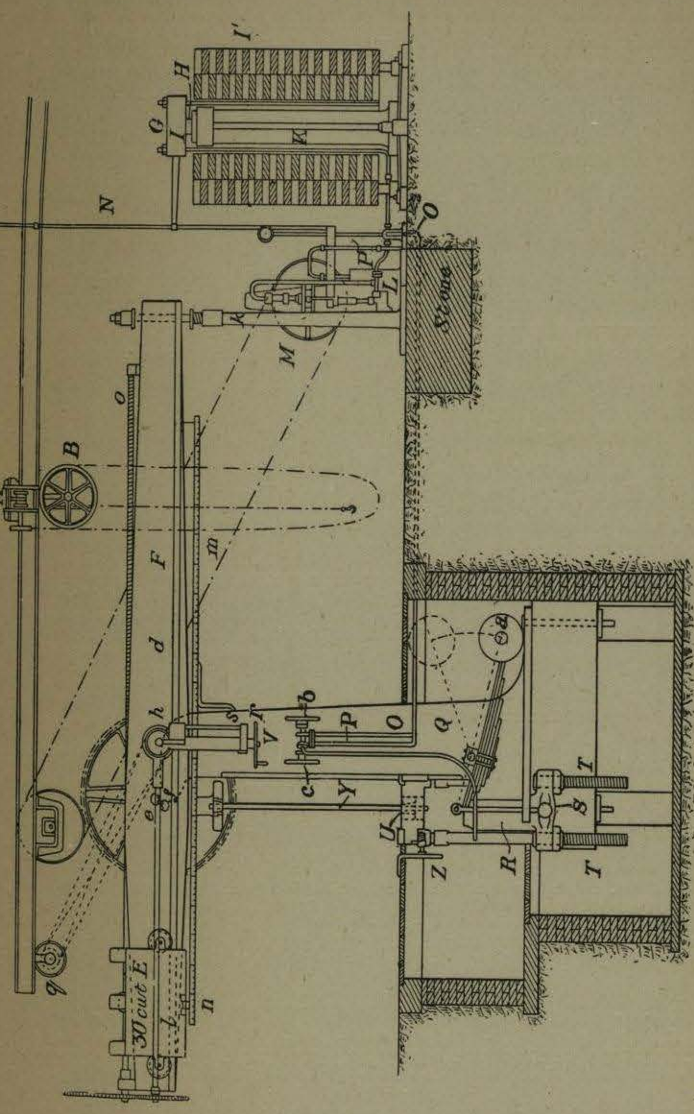

FIG. 9.—Wicksteed Testing Machine, Bradford College. A, small overhead traveller; B, 2-ton pulley blocks; E, travelling poise-weight; F, main lever; G, accumulator; H, accumulator ram; I, crosshead to ram carrying weights; K, cylinder of accumulator; L, pump for supplying accumulator; O, pressure pipe from accumulator; P, exhaust pipe to accumulator; Q, main cast-iron standard; R, hydraulic straining cylinder; S and U, crossheads attached to hydraulic ram; T T, strong screws connecting crossheads S and U; Z, worm gearing for operating screws T; *a*, balance-weight; Y, specimen; *b*, pressure valve; *c*, exhaust valve; *e*, knife-edge fulcrum for F; *f*, knife-edge for shackles; *m*, graduated scale; *n*, vernier; *o*, screw for moving poise-weight; *q*, counter shaft; *r*, hand-wheel for slow movement of E; *s*, reversing handle.

The main lever or steelyard, F, is double-ended, made of cast iron, and turns on a knife-edged main fulcrum, *e*, on the top of the main standard, and from a second knife-edge, *f*, hangs the upper shackle which carries the gripping-box for the upper end of a tension specimen, or from it may be suspended, by means of four strong rods, a table having a face for the bottom end of a compression specimen when the machine is used for these tests.

The knife-edges are of hardened steel, 20 inches long, and the fulcrum distance between them is 3 inches. The motion of the end of the lever is limited by stops, fitted with strong steel springs on the post, *k*. The travelling poise-weight, E, of 30 cwts., is of rectangular form, overhanging the sides of the main lever, so that its centre of gravity may be kept on the plane passing through the knife-edges. The graduated scale, *m*, is 200 inches long, reading 2 inches to the ton, and is carried upon brackets depending from the side of the lever. The vernier, *n*, which easily reads to $\frac{1}{100}$ ton, is carried by the poise-weight, and its position is adjustable, so that when the lever has been put in balance it may be set to zero on the scale. The actual weight used for measuring the stress is double the weight of the poise, viz. 3 tons, and a leverage ratio of 33·3 to 1 is obtained.

The poise-weight is mounted on four rollers, which run on rails cast on the sides of the lever, and it is moved by a quick-threaded screw, *o*, which is rotated by spur wheels from a shaft fitted with Hooke's joint to allow of the motion of the lever, in connection with the reversing gear, *p*, driven by open and cross belts from the countershaft, *q*. A hand-wheel, *r*, is also provided for very slow motion or fine adjustment, and this, together with the reversing handle, *s*, and hydraulic valves, *b* and *c*, is placed within easy reach of the operator, who, without moving from his position, has the specimen in full sight, and can easily observe the movement of the lever. A small overhead traveller, A, is provided, actuated by hand-chains, fitted with a 2-ton pulley block, B, for moving large specimens and for lifting different parts of the machine.

In a testing machine it is extremely desirable to have some apparatus by the aid of which the stress-strain diagram of a piece of metal under test may be drawn automatically. Several types of apparatus of this kind have been devised. In the one by Wicksteed[1] (fig. 10), the motion of the pencil that indicates the load is derived from the pressure in the hydraulic press, and not from the weighing apparatus, a wire attached by clips to the specimen serving to rotate a recording drum by an amount proportional to the elongation. The pencil having an axial motion proportional to the load, and the drum a rotating motion proportional to the extension, a stress-strain diagram is described.

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[1] *Inst. Mech. Eng. Proc.*, 1886, p. 27. For descriptions of American machines consult *Testing Machines: their History, Construction, and Use*, by A. V. Abbott, New York, 1884.

This apparatus has been improved in several particulars by Unwin.

Details of Tests.—The test bar may be of any convenient size, and either round or rectangular in section, but a circular bar is distinctly the best, as it can be more accurately gauged after fracture for the determination of the contraction of area. In the case of plates or bars, however, circular bars are generally impracticable, and a parallel strip of plate, as rolled, either shouldered down at each end or not, may be used.

The test piece having been carefully machined to the required shape, it is accurately gauged, preferably with a delicate screw micrometer, in at least three places along its length, and, if anything but a cylindrical bar, both the width and thickness taken; and from the mean of these measurements the area is calculated. A very fine line is then drawn with a scriber along the surface of the bar, preferably along the centre of the wide side of a flat bar, and on this any distance, varying from 2 to 8 or 10 inches, according to the length on which it is desired to take the elongation, may be marked off by means of two very small punch-marks.

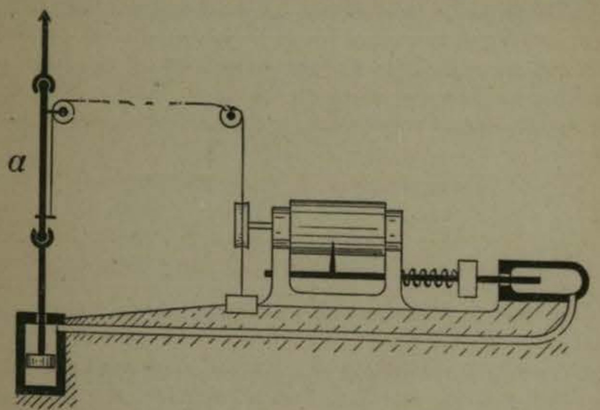

FIG. 10.

The test bar is then placed in the machine and the pressure applied until the beam lifts, when the weight is cautiously advanced along the beam to keep it floating in the horizontal position, measuring between the two stops on the top of the small standard *k* at the end of the beam (fig. 9). After the load reaches a certain point, the bar will suddenly elongate and, almost immediately, without any increment of load, the beam will drop on to the bottom stop: this is known as the yield point, a point just beyond the true elastic limit: the load at this point is read off, and if the pressure be continued, the beam will rise again and the weight will have to be advanced to keep the beam floating in the horizontal position between the stops until a point is