THE MAGNETISM OF PERMANENT MAGNETS.

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[*Lecture delivered at the Glasgow Meeting of the Institution on 13th June, 1912.*]

SUMMARY OF CONTENTS.

FOR CONSTANCY AND POWER OF PERMANENT MAGNETS it is necessary to consider the following points:—

1. QUALITY OF STEEL : Carbon Steels; Alloy Steels; their percentage composition.
2. SHAPE AND DIMENSIONS : Bars, Short and Long; Shapes forming Nearly Closed Curves.
3. HEAT TREATMENT : Normalizing; Quenching; Temperature of Quenching; Rapidity of Quenching; Tempering.
4. MAGNETIZING : Methods; Appropriate Intensity of Field.
5. MATURING : By Lapse of Time; by Mechanical Shock; by Reheating; by Partially Demagnetizing.
6. CONSERVING : Safeguards for Conservation.

INTRODUCTORY.

It is impossible, at any rate for me, to come back to the University of Glasgow without referring to the late Lord Kelvin, from whom we have learned so much in this subject of Magnetism. Alas! he is no longer here to represent science in the University.

The magnetism of permanent magnets is a subject which interests all electrical engineers; but I doubt whether the majority of them recognize the real importance of it. In many diverse instruments everything depends on the constancy of permanent magnetism: and that constancy, now habitually attained to a remarkable degree, has not been reached without labour and long effort. We have all been familiar from our boyhood with magnets, but I doubt whether any of us has realized the number of problems which in the developments of the last twenty years have been confronted, investigated, and solved. But I have ventured to think that if one might collect the scattered data that have been gleaned in the researches of many workers during those years, and put them, as they have not hitherto been put, into a collected whole, the result would be worth recording, even though, as in the present case, the individual who has had the labour of putting the data together has practically nothing to claim in the way of originality upon his own part.

I have to speak, then, not of my own researches, but of things that have been done by other investigators in this and other lands.

Now in the first place, it goes without saying that we consider the materials which are proper for the making of permanent magnets, and, primarily, of *steel.* For all ordinary purposes there are no permanent magnets except those made of steel. I do not, of course, forget that there is also the material lodestone ; nor am I oblivious of the circumstance that Professor Pierre Weiss has lately discovered a new magnetic material, an alloy of cobalt and iron, which appears to possess the property of acquiring a larger degree of magnetism than any other substance, and of retaining it to a remarkable extent. But it must suffice here to note that there is such a material, since its properties require further investigation. We have therefore to deal only with steel. Let me enumerate the heads under which we shall have to consider steel. First there are the questions of the composition and constitution of the steel. Ought we to use carbon steel or an alloy steel ? If carbon steel, what percentage of carbon should we adopt ? Remember that our word "steel" does duty as the name of materials which differ enormously in their mechanical and chemical properties. Formerly, when people were beginning to distinguish between iron and steel, they used to reserve the name "steel" for those kinds of iron which could be hardened by quenching, so as to take an edge when ground for service as weapons or tools, and which when duly tempered showed the valuable property of elasticity, making them useful for springs. All other kinds they called "iron," whether of the soft ductile and malleable sort containing practically no carbon, known as "wrought iron," or whether of the harder and more brittle kind containing more than 2 per cent of carbon, known as "cast iron." But in the nineteenth century the great metallurgists discovered new ways of making a nearly pure iron, capable of being cast, often containing less than a tenth of 1 per cent of carbon, nearly as soft, as ductile, and as malleable as wrought iron. Yet simply because a material called "steel" fetches a higher price in the market than a material called "iron," they gave to this remarkably pure iron the name of steel—"mild steel." Without falling into the verbal pitfall thus provided, let us say simply that for the purpose of making magnets the steel that we must use is one that is really *steel,* in the old sense. That is to say, it will be no good for making magnets unless it is capable of being hardened by quenching. A soft steel is useless for this purpose. But the hardenable steels comprise two groups of material ; the high-carbon steels, containing from 0·3 to 1·5 per cent of carbon, and the alloy-steels containing, along with a certain percentage of carbon, a notable quantity of one of the metals tungsten, molybdenum, chromium, or vanadium. To one or other of these classes magnet-steels belong ; and it will be necessary to consider them in detail.

A second consideration, and one which will to some extent affect our choice of material, is the question of the shape and dimensions of the magnet that is to be made. It will be made abundantly clear that the magnetic properties of short bar-magnets, and of magnets of any short shapes, such as cubes or spheres, are very different from those which have the form of long bars, or which are bent round in circles or horse-shoes so as to form nearly closed shapes. And it does not follow that the material which is suitable for a long bar magnet or a horse-shoe will be suitable for short magnets such as are occasionally wanted.

Then there is a third consideration of a metallurgical nature, namely, the heat-treatment to which the material has been subjected at the steel works. Steel of a given composition may differ widely in its magnetic properties according to the furnace processes to which it has been subjected. Before it receives its shape it has been subjected to various heatings and coolings, as well as to mechanical processes of hammering, or drawing, or forging. Its homogeneity of structure depends on these : but it also depends on the heat-treatment that the magnet receives after having been brought to its final shape. If we are to know how to make magnets which are as powerful and as constant as possible, we must know to what temperature they should be heated before we quench them, and how long they should be so heated. We ought to know at what temperature they should be quenched to harden them, and how rapidly they should be quenched. Further, we ought to know whether after this hardening there is any advantage or disadvantage in reheating them to temper them.

A fourth consideration is the process of magnetizing them : in what magnetic field, or how? Happily this is the least troublesome of all the processes, because if you have a sufficiently powerful electromagnet to impart the magnetism, the precise mode of applying it is an unimportant issue. The magnetism which a magnet retains permanently is only a fraction, it is true, of the magnetism temporarily imparted during magnetization : but if the temporary magnetization has already been pushed to a high degree, there is little or no permanent advantage to be gained by pushing it further to abnormal values.

Fifthly, after a magnet has been magnetized, and if it has to be brought into such a state that its permanent magnetism is really constant, it must be subjected to a further process of maturing.*

Lastly, there is the question of conserving the magnetism of a magnet. Let me dispose of this, once for all. The only way to conserve the constancy of a magnet which has been prepared through all the series of processes is to see that it is never subjected either to severe heating or cooling, and never allowed to touch against any

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* This process of "maturing" must be carefully distinguished from the effect, sometimes called "ageing," which occurs in transformer iron. Ageing is the term properly applied to the phenomenon which sometimes occurs in a transformer, when the sheets of iron used for the core show impaired permeability and increased hysteresis after use for a few months. The maturing of magnets may occur naturally during the first few months or years after their magnetization, as they settle down to constancy. This process of settling down may be hastened in several ways : by mechanical shock, by repeated steaming or warming, or by partial demagnetization. The term "maturing" appropriately includes all varieties of the process. Some of the operations of maturing the steel may be effected even before magnetization.

other magnet or piece of iron. The supposed safeguard of putting on a keeper is about the worst device ever suggested. Every time the keeper is suddenly put on the magnet is weakened. Every time it is suddenly pulled off the magnet is strengthened.

Magnetic Qualities of Steel.

I resume the consideration of the separate questions which have now been stated : and foremost that of the quality of the steel. Here we have the magnificent series of researches associated with the names of Sir Alfred Ewing, the late-lamented Dr. John Hopkinson, the brothers Professors Andrew and Thomas Gray; and in more recent times those of Messrs. Barrett, Brown, and Hadfield, those of Sir Robert A. Hadfield on the alloy steels; and those of Messrs. James G. Gray and Alexander D. Ross, to name no others.

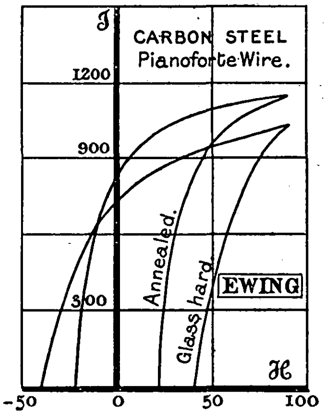

Fig. 1.—Hysteresis Loops (Ewing).

The researches of Ewing and of Hopkinson are so well known that a very brief reference to the salient points which their work brought out must suffice. When any specimen of steel is subjected to magnetizing forces it acquires a temporary magnetization in excess of that which it retains when the magnetizing force is removed; and, of the magnetism which remains, a part only is retained permanently, a considerable part being readily removed by any demagnetizing forces to which it may be subjected. It is a commonplace to say that the softer the specimen the less is the fraction of magnetism which it retains permanently, and the harder the specimen the greater is that fraction. But the amount which remains when the magnetizing forces are removed is, in different specimens, held in the steel with different degrees of fixidity. Following Hopkinson, we take as a measure of the tightness with which the magnetism of a specimen is retained the amount of demagnetizing magnetic force which must be applied in order to reduce the magnetization to zero. And the "coercive force," or fixidity, is defined as equal (and opposite) to that amount of demagnetizing force.

Let us illustrate the matter by a diagram (Fig. 1), taken from Ewing, relating to a carbon steel wire which was magnetically tested in an annealed state, and again tested after having been made glass-hard by quenching when nearly at a white heat. Comparison of the two hysteresis loops shows that the soft steel, when subjected to a magnetizing force of about $\mathbf{H} = 100$, acquired a magnetic flux-density having a value of $\mathbf{B}_{max.} = 14500$; the value of the intrinsic magnetization being $I_{max.} = 1145$. When the magnetizing force was reduced to zero the residual value of B fell* to about 10400, or $I_{rem.} = 827$; and it required a demagnetizing force of about $H = -22$ to reduce the residual magnetism to zero. In the hard state an application of the same magnetizing force produced a flux-density of about $B = 12600$ only, which fell to about 9600 on the removal of the magnetizing force. But the demagnetizing force required to reduce the flux-density to zero was now $H = -40$. Stated otherwise, the hard steel showed actually a lower value of the remanence $I_{rem} = 764$, as against 827 for the soft steel; but this lesser amount of residual magnetism was held more tightly, since the coercive force for the hard steel was 40 as against 22 for the soft steel.

It will be convenient here to present a Table in which are collected together a number of similar data for various specimens that will be referred to in the course of this lecture.

The hysteresis loop provides us then with the means of defining the two most important facts that we ought to know about any steel that is to be used for making permanent magnets—the value of the remanent magnetization and the value of the coercive force: the height of the point where the curve crosses the vertical axis, and the breadth of the loop on either side of the zero-point. And of these two things by far the most important is the latter—the coercive force. We shall consider any steel to be unsuitable for modern requirements if it does not have the value of I_{rem} at least as high as 800, or if the value of H_c does not exceed at least 60.

Our next question is how the carbon content of a steel affects these two properties. It is well known that low-carbon steels do not harden appreciably on being quenched; and, broadly speaking, we may say that a carbon steel containing less than a quarter of 1 per cent carbon does not harden. Neither is such a steel of the slightest use for a permanent magnet. Carbon steels containing from 0·75 to 1 per cent of carbon, known as die-steels, sett-steels, and chisel-steels, are suitable for such articles as stamping dies, hammers, miners' drills, chisels, shear-blades; those containing from 1 to 1·15 per cent for drills, milling cutters, screwing dies, which require a greater hardness; those containing 1·25 per cent for turning tools, fine drills, small milling cutters, which must be capable of still further hardness; 1·5 per cent for razors, fine turning tools, and files, which have to be extremely hard. The hardness which they can acquire on quenching increases with the carbon content.

The hardening produced by carbon is, in fact, up to a content of

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* In considering other hysteresis loops I shall, for brevity, denote the remanent value of B by the symbol B_{rem}, and the value of H which measures the coercive force as H_c. For the purpose of this lecture it will be convenient to plot the intrinsic magnetization I, rather than of the flux-density B; the residual magnetization, or "remanence," being then denoted as I_{rem}. Since $I = (B - H) \div 4\pi$, and H is almost always small compared with B, we may consider approximately $I = B \div 4\pi$. As the values of B_{rem} run over a range of from about 6000 to 11500, those of I_{rem} will run from about 500 to about 900 in such steels as come into our consideration.

DATA OF MATERIALS MAGNETIZED WITH A MAGNETIZING FORCE OF H = 100, OR UPWARDS.

Material.	Percentage Carbon.	Percentage Tungsten.	State of Hardness.	$B_{max.}$	$B_{rem.}$	$I_{rem.}$	H_c.	Authority.
Swedish wrought iron ...	trace	—	Very soft	17400	6900	550	0·80	Du Bois and Taylor Jones
Softest selected iron... ...	trace	—	Very soft	17430	10400	804	0·44	Kamps
Piano steel wire	0·95 (?)	—	Annealed, soft	14500	10400	824	22·00	Ewing
Piano steel wire	0·95 (?)	—	Glass-hard	12600	9600	760	40·00	Ewing
Low-carbon steel	0·06	—	Quenched at 1000° C., soft	19800	7812	625	3·40	Mme. Curie
High-carbon steel	1·20	—	Quenched at 800° C., hard	15080	8060	645	58·00	Mme. Curie
Haarlem magnet steel ...	—	—	Hard	16900	10048	800	56·00	Du Bois and Taylor Jones
Allevard steel	0·59	5·50	Not quenched	18700	11250	900	26·00	Mme. Curie
Allevard steel	0·59	5·50	Quenched at 770° C.	17500	10500	800	73·00	Mme. Curie
Böhler's Styrian steel... ...	—	—	Soft	17850	9950	790	34·00	Du Bois and Taylor Jones
Böhler's Styrian steel... ...	—	—	Hard	14000	7570	600	75·00	Du Bois and Taylor Jones
Remy tungsten steel ...	—	—	Hard	15145	10157	808	63·00	Eichel
Remy tungsten steel ...	—	—	Very hard	16070	10040	800	77·00	Du Bois and Taylor Jones
Medium tungsten steel ...	0·89	3·08	Quenched at 760° C., hard	11000	7330	572	58·80	Swinden
Whitworth tungsten steel ...	0·51	4·01	Quenched at 900° C., hard	—	—	610	37·00	J. G. Gray and A. Ross
Molybdenum steel	1·25	(Mo) 3·36	Hard (δ = 23)	10000 (?)	4651	370	85·00	Mme. Curie
Chilled cast iron	—	—	Chilled at about 1000° C.	9000 (?)	1775 1850	218 229	52·80 51·10	Campbell Campbell
Lodestone	—	—	—	—	—	350	50·00	Du Bois

1 per cent, proportional to the amount of carbon present. And so, also, broadly speaking, is its coercive force. Later on I shall refer to some important investigations by Mme. Curie on the alloy steels: but she made also some highly significant measurements on carbon steels. Fig. 2 gives two hysteresis loops determined by her. The one marked A relates to a low-carbon steel containing only 0·06 of 1 per cent of carbon, and was therefore practically a pure iron. The other, marked B, was a fairly high-carbon steel containing 1·2 per cent of carbon. Both had been quenched, B at about 800° C., when it hardened; A at about 1000° C., which, however, did not harden it. It will be seen that for both kinds the value of I_{rem} was nearly alike, being 625 for the low carbon and 645 for the high-carbon steel; but the low-carbon steel held its magnetism very loosely, the coercive force being only about 3·4; while the high-carbon steel held its magnetism much more fixedly, the coercive force being about 58. According to Professor Arnold, though the magnetic permeability of a specimen is inversely proportional to its carbon content, the amount of permanent magnetism retained is directly proportional to the carbon content.* This statement is not true of the values of I_{rem}; but is more nearly true of the values of the coercive force. The next diagram, Fig. 3, is due to Dr. Carl Benedicks, and shows the variation of the coercive force with the carbon content. From this we see that the mild steels having less than 0·25 of 1 per cent of carbon have very little coercive force; but that the coercive force increases between 0·5 and 1 per cent, and at 1·15 per cent carbon content reaches a value of about $H_c = 50$. Obviously this affords a first reason why high-carbon steels make far better permanent magnets than do the low-carbon sorts.

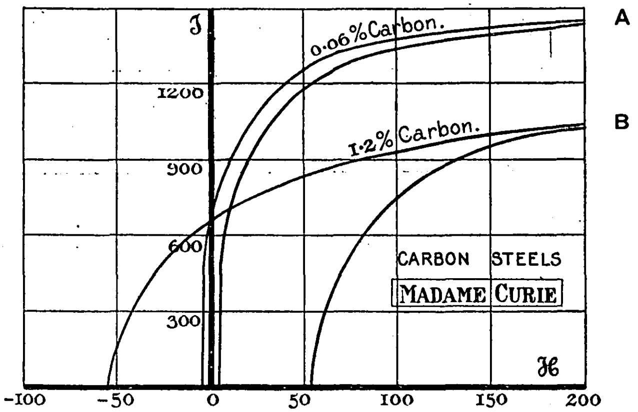

FIG. 2.—Hard and Soft Carbon Steels (Mme. Curie).

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* Arnold regards the constituent hardenite (see p. 103) as a definite subcarbide of iron, of composition $Fe_{24}C$; and holds that the permanent magnetism depends upon the amount of this substance present.

But it has been known for many years that certain steels containing other constituents beside carbon possess special qualities both as respects hardness and as respects magnetic fixidity. The sort known as Mushet's steel, the earliest of the great class of tool steels, was found to remain hard even when very hot; and when forged it was self-hardening without having to be quenched in cold water. It was found to contain* from 7 to 12 per cent of the metal tungsten, besides having from $1\frac{1}{2}$ to 2 per cent of carbon. In recent years many varieties of self-hardening tool steels have been produced by metallurgists, some containing tungsten, others containing other metals such as molybdenum or chromium, also manganese or vanadium. All such steels belong to the class to which the generic name of *alloy steels* is given, to distinguish them from the pure carbon steels. The alloy steels may or may not contain carbon; and they vary enormously in their properties. Aluminium steel and silicon steel are very soft; and, as Sir William Barrett has shown, may even surpass pure charcoal iron in having a great permeability and very little coercive force. Manganese steel is very hard, and, curiously, is almost non-magnetizable. Many of these alloy steels are coming into use in the industries; and their introduction has opened out a new branch of the steel industry. Magnetically several of them are of extreme interest. For many years it has been known that a particular kind of steel coming from the forges of Allevard, near Grenoble, made most excellent permanent magnets. The Allevard steel is a tungsten steel containing about $5\frac{1}{2}$ per cent of tungsten and about 0·59 per cent of carbon. Fig. 4 shows the tests made by Mme. Curie on a specimen of Allevard steel. Curve A shows the magnetic behaviour of the specimen as received from the forge, not specially annealed, neither specially hardened. Curve B shows its behaviour after being heated to 770° C. and quenched at that

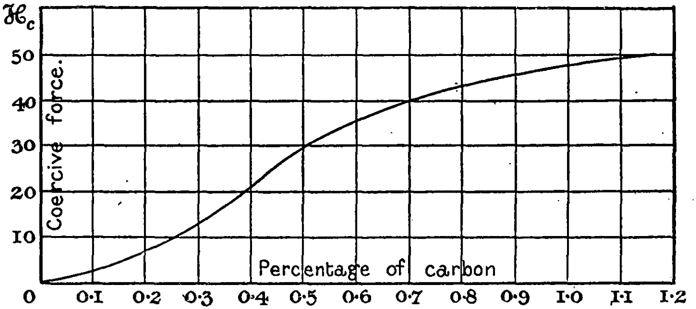

FIG. 3.—Variation of Coercive Force with Percentage of Carbon (Benedicks).

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* The Mushet steel manufactured by Messrs. S. Osborn & Co. has, on the average, 5·8 per cent of tungsten, 1·65 carbon, 2·12 manganese, 0·45 chromium, and 1·36 silicon. B. E. Jones gives 8·22 tungsten, 2·3 carbon, 1·72 manganese, and 1·6 silicon.

temperature in cold water. The value of I_{rem} was decreased from 900 to 800, and the coercive force was increased from 26 to 74, by quenching.

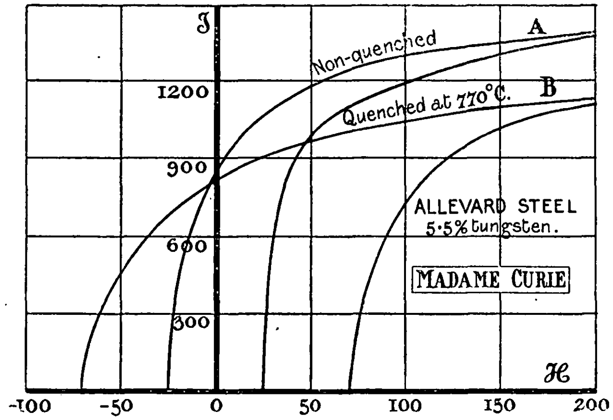

FIG. 4.—Unhardened and Hardened Tungsten Steel (Mme. Curie).

Many steel-makers now make special magnet steels, using alloys of tungsten and other metals. Magnet steels can be obtained from various Sheffield firms: Messrs. W. Jessop & Sons; Messrs. Edgar Allen & Co.;

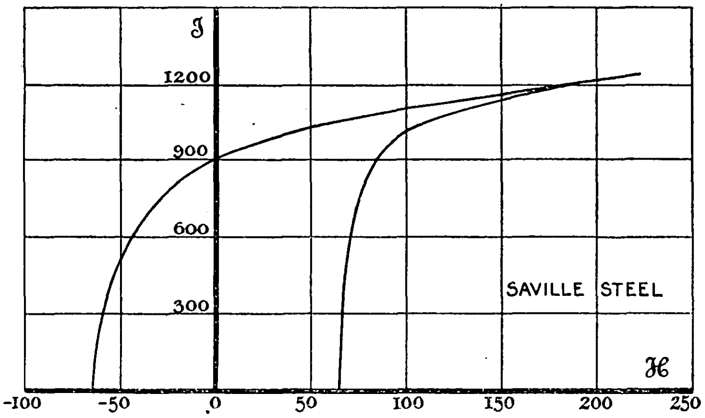

FIG. 5.—Saville's Tungsten Steel (Hardened).

Messrs. Seebohm & Dieckstahl; Messrs. S. Osborn; Messrs. J. J. Saville & Co.; Messrs. T. Firth & Sons; as well as from certain Continental firms such as Heinrich Remy, of Hagen in Westphalia; Ch. Pinat & Cie, Allevard, Isère; and Messrs. Böhler Brothers, of Kapfenberg and Vienna. An example is afforded by a tungsten steel of Messrs. J. J. Saville, of Sheffield, Fig. 5, which has a remanence

$I_{rem} = 917$, and a coercive force of 65, which exceeds that of any carbon steel. I shall return to questions affecting the alloy steels later on.

MODERN METALLURGICAL VIEWS ON STEEL.

But if modern metallurgy has taught us that the chemical composition of the steel is important, it has also taught us that there is something equally important, namely, the constitution or structure of the steel. Perhaps no advance in recent times has had an importance comparable with that connected with the application of the microscope to the study of metallic structures. The science of metallography, founded by Sorby, and extended by Ewing, Roberts-Austen, Stead, Rosenhain, and Beilby in this country, and by Osmond and many other workers on the Continent, is revealing the interior secrets of the metals and alloys. As the result of micrographic researches steels are known to contain certain structural constituents known as ferrite, cementite, pearlite, martensite, hardenite, austenite, etc., which can be recognized in the microscope. Of these, ferrite appears to be—in the carbon steels at least—pure iron in small definite crystals; and cementite appears to be a definite carbide of iron Fe_3C. Pearlite, so called from its nacreous lustre, is that particular mixture of constituents which has the lowest transformation point, and which, remaining mobile in the solid mass down to about the temperature of 690° C., is the "eutectic" * (or most fusible) of all possible of the carbon-iron alloys. It has a composition of about 0·9 of 1 per cent of carbon to 99·1 per cent of iron. If a (mild) steel containing less than this percentage of carbon is heated to its melting-point, and allowed gradually to cool, its solidification begins by some ferrite (pure iron) freezing out and forming crystals throughout the plastic mass; which crystals grow at the expense of the rest until the remaining mobile part has reached the percentage of pearlite, when it all solidifies, the ferrite crystals being found enclosed in a surrounding matrix of pearlite.† On the other hand, if a high carbon steel containing over 0·9 per cent of carbon is melted and allowed to cool, cementite will be formed first, and as the solidified mass cools, the percentage of carbon in that part which is still in a mobile state, will fall until the percentage of pearlite is reached, when all the enclosed residue becomes solid, the masses of cementite being then found to be surrounded by a matrix of pearlite. But if the cooling instead of being gradual is sudden, other changes occur, differing with the proportions of carbon present, and with the suddenness of the cooling. In high carbon compositions rapid cooling results in the formation of characteristic structures which influence the mechanical properties. Thus martensite is a constituent which usually exhibits a structure apparently consisting of interlaced needle-like crystals, making the steel very

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* Howe's term *æolic* is certainly preferable here to the more commonly used term *eutectic*. For while *eutectic* properly signifies most fusible, we have here to deal with a solid undergoing transformation, and with a composition that has lowest temperature of transformation.

† At this point in the lecture a number of micrographic photographs were projected upon the screen in illustration of these metallographic discoveries.

strong, as required for steel rails. The hard constituent called hardenite (which may be a solid solution of carbon in iron, or possibly a subcarbide of iron) is of the same percentage as pearlite, and is formed during any cooling that is so rapid that the particular pearlite structure has not time to form. This constituent appears to be the most important one in magnets. Another structure called austenite, which consists of zigzag streaks in a mass of hardenite, appears to be a pure 1·6 per cent carbon steel, a solid solution of carbon or of cementite in the rest of the steel. The subject is so wide that it is quite impossible here to give any adequate summary of it: suffice it to say that metallurgists have sought to explain, from the properties of these constituents, the mechanical properties of different kinds and qualities of steel, and to account for the phenomenon of mechanical hardening. But the matter does not stop here. Certain lines of reasoning have led to the hypothesis that iron itself can exist in three different states, or phases, which some regard as allotropic forms; and these pass spontaneously into one another by mere change of temperature. Pure iron at ordinary temperatures is soft and highly magnetizable, and is called Alpha iron. When heated to about 750° C. it passes into

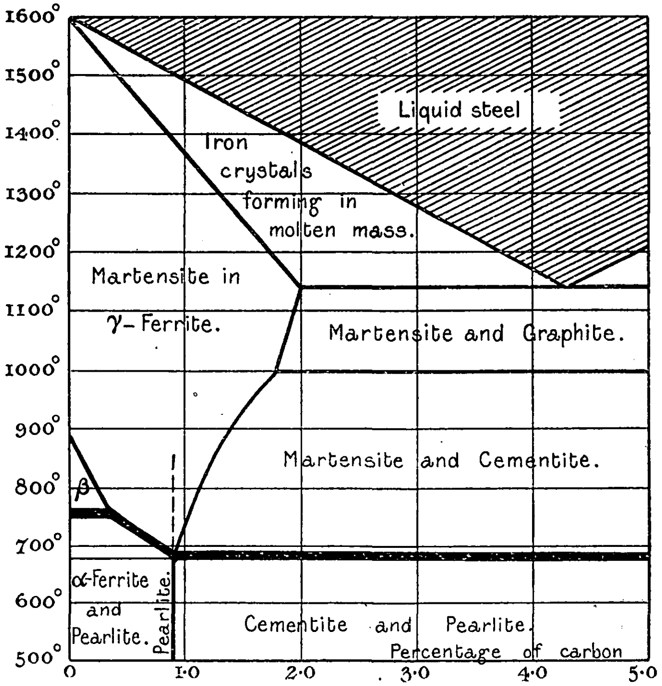

FIG. 6.—Diagram of Equilibrium States of Carbon Steels at Different Temperatures.

the Beta state, in which state it is rather harder and non-magnetic. When heated to about 860° C. the Beta iron passes into the Gamma state (also non-magnetic). On cooling the changes occur in the reverse order. Fig. 6, which is due to Roberts-Austen,* modified by Roozeboom and others, summarizes the foregoing matters in a graphic way. In this diagram the percentage of carbon in the steel is plotted horizontally, from 0 (pure iron) on the left to 5 per cent (cast iron) on the right. Temperatures up to 1600° C. are plotted vertically. For ordinary steels containing from 0 to 2 per cent, the melting-point lies between 1600° and 1380° according to the carbon content. Below these temperatures, for some way down the diagram, the material is plastic consisting of gamma-ferrite mixed with martensite, or (if a greater proportion of carbon is present) of martensite mixed with cementite. As the plastic stuff cools its constitution alters; the various regions of the diagram indicating the state that is stable at the various temperatures. A steel with the particular composition of 0·9 per cent of carbon (indicated by the dotted vertical line) is that which remains homogeneous, or unsegregated, to the lowest temperature, namely, about 690°, when it changes into pearlite.

Now we wish to connect these metallurgical discoveries with the magnetic properties of the steels. The first and most notable connection is indicated by the thick line which runs nearly horizontally across the diagram. It marks the temperatures at which the steels of different percentage composition cease to be magnetic. Steels of every kind when heated above about 700° C. cease to be magnetic. That is, they are not attracted by a magnet, and cannot act as magnets. They all, with certain rare exceptions, regain their quality of magnetizability when cooled down again below that temperature. For all high-carbon steels the temperature is from 680° C. to 690° C.; for low-carbon steels a little higher; and for pure iron itself about 760° C. The consideration of this matter will be resumed under the head of heat-treatment.

EFFECT OF SHAPE AND DIMENSIONS.

It has long been known that, for a given material, long bars are more retentive than short ones; and that nearly-closed forms such as horse-shoes, or rings with a slit across them, are more retentive than forms that have their ends widely apart. Nearly forty years ago, as I remember, Lord Kelvin taught us that short bars have no magnetic memory. Squat forms such as short cylinders, cubes, or spheres, even if made of the hardest and best steel, have surprisingly little retentivity. Long bars of soft stuff usually keep much more magnetism than do short bars of hard steel. The reason is that the poles of every magnet exercise a self-demagnetizing influence on the body of the magnet: and this self-demagnetizing influence depends both on their shape and on their strength. The self-magnetizing effect is best dealt with by means of a

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* Fourth Report of Alloys Research Committee. *Proceedings of the Institution of Mechanical Engineers*, Parts 1 and 2, p. 70 and p. 90, 1897.

self-demagnetizing coefficient or factor, which in the case of cylindrical bar-magnets depends only on the ratio that the length bears to the diameter. That ratio, the so-called dimension-ratio, is, as you will presently understand, of immense influence upon the qualities of the magnet. In a bar magnet the poles are continually acting on one another, and exercising demagnetizing forces on the parts of the magnet that lie between them. The shorter the bar, the nearer together are its two poles, and the greater the demagnetizing action which they exert on the steel in the middle of the bar. Let H_d stand for the demagnetizing field due to the poles ; its value is found to be proportional to the intensity of the intrinsic magnetization I. We may, then, write $H_d = D \times I$; where D is the coefficient of demagnetization ; and obviously it may be stated as $D = H_d \div I$. It is possible to determine the values of D for cylindrical magnets of different lengths and thicknesses by pure experiment. It is also possible to predetermine them by theoretical calculations from the properties of ellipsoids, though approximately only. Various persons, including Sir Alfred Ewing, Professor Ascoli, Professor Du Bois, Dr. Riborg Mann, and Mr. C. L. B. Shuddemagen, have determined their value. The most recent figures are those published by myself * and my former assistant, Mr. E. W. Moss. Our

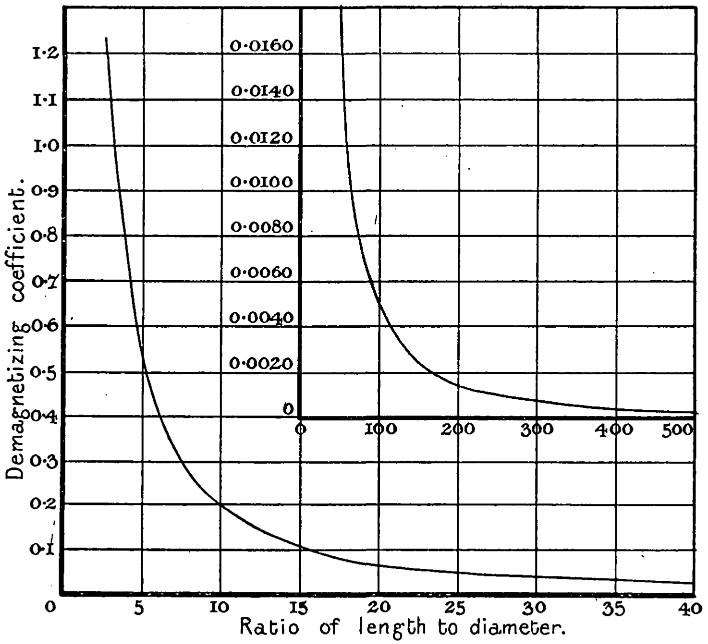

FIG. 7.—Dimension-ratios and Demagnetizing Coefficient.

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* *Proceedings of the Physical Society of London*, vol. 21, p. 622, 1907–9.

figures, which agree closely with those of the earlier investigators, were undertaken to extend the measurements to shorter bars, and bars of rectangular section. Fig. 7 gives graphically the values of the demagnetizing coefficient as it falls from 1·2, for rods that are 2·66 diameters long, to 0·0223 for rods that are 40 diameters long. Numerical values are given in the following table, in which the values for rods that are more than 40 diameters long are taken from the dissertation of Riborg Mann.

Dimension-ratio, δ	2·5	2·66	3·55
Demagnetizing Coefficient	1·3	1·2	0·83

l/d	4·44	5	5·34	6·66	8·86
D	0·618	0·53	0·483	0·352	0·233

l/d	10	13·3	15	17·72	20
D	0·198	0·129	0·108	0·0826	0·069

l/d	25	30	35·6	40	50
D	0·0438	0·036	0·0255	0·0223	0·0182

l/d	60	70	80	90	100
D	0·0131	0·0099	0·00776	0·00628	0·00518

l/d	150	200	300	500	1000
D	0·00251	0·00152	0·00075	0·00018	0·00005

Passing on to the case of slit rings, it has been shown by H. Lehmann and H. Du Bois that the demagnetizing effect of a slit in a ring magnet is nearly proportional to the width of the slit, that is to say, to the width of the gap in the magnetic circuit. It would be precisely proportional if there were no magnetic leakage, and if the gap itself were small compared with the radius of the ring. The demagnetizing coefficient is, in fact, about 0·035 per degree of the width of the slit. But if the ring, instead of being merely slit, is provided with enlarged pole-pieces which approach one another, so as to leave a narrow gap between the two polar areas, the demagnetizing coefficient may be very greatly reduced. Fig. 8 represents diagrammatically such a magnetic circuit, with enlarged polar surfaces. The dotted line represents the mean path of the flux along the magnet core. Let this length be called l_m, and let the width across the gap be called l_g. Let the area of cross-section of the magnet core be called A_m, and the area of cross-section of the flux at the gap—practically the same as the area of either pole-face—be called A_g. Also, let ν denote the coefficient of allowance for magnetic leakage, that is, the ratio of the total flux in the magnet core at its middle to the useful flux in the gap. Then, in terms of these quantities the demagnetizing coefficient may be written—

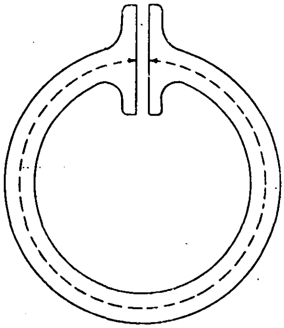

FIG. 8.—Theoretical Magnetic Circuit.

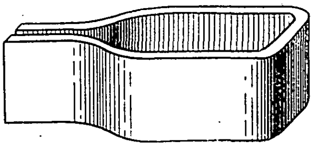

FIG. 9.—Form of Magnet used in Thomson-Houston Meter.

$$D = -\frac{4\pi}{\nu}\left\{\frac{l_g}{l_m}\cdot\frac{A_m}{A_g}\right\}$$

From this it appears that the tendency to self-demagnetizing may be reduced at will by making A_g large or l_g small, or by providing a large magnetic leakage. In 1888 Hookham pointed out the significance of the ratio above enclosed in brackets, and gave the empirical rule* that for magnets that should be both powerful and constant that ratio should not exceed $\frac{1}{10}$. But with modern steel, and with allowance for magnetic leakage, higher values may be permitted.

As an example may be cited a magnet of the form shown in Fig. 9

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* Mr. Hookham, writing in 1912 to the author, in reply to a query whether he considered this rule to be still adequate, said that having been indirectly experimenting on it, ever since 1888, in the application of it to magnets in hundreds of thousands of meters, he has found it a safe law. He adds: "It is really a rule for using the steel to the best advantage—for producing the most intense permanent field in an air space of given distance between poles and given cross-section with the greatest economy of steel. If magnet steel improved in quality, *i.e.* in retentive power, the length of magnet might be reduced ; but there has been no appreciable improvement —I doubt if there has been any."

used in the Thomson-Houston meter. The values measured were: A_g, 84 sq. cm.; A_m, 2·1 sq. cm.; l_g, 0·375 cm.; l_m, 24·5 cm.; and ν was ascertained by experiment to be 1·35. Hence for this magnet $D = 0{\cdot}00358$, which is the same as for a rod 130 diameters long, or as for a plain slit ring having a slit only $\frac{1}{10}$ of a degree wide.

Professor Ascoli, of Rome, who has devoted much attention to the permanency of magnetism, has suggested a graphic method of handling the question of the degree to which the residual magnetism of a magnet is reduced by this self-demagnetizing action. If, neglecting magnetic leakage and the resulting variations of I along the body of the magnet, we assume a uniform mean value, and if we also assume that the demagnetizing coefficient of a given magnet is a constant at all stages in the cycle of magnetization, we may then ascertain the intensity of the demagnetizing field at any stage as follows:—

In Fig. 10, let the values of I for any given steel be plotted against the values of **H**, giving the usual loop curve, as determined for a very

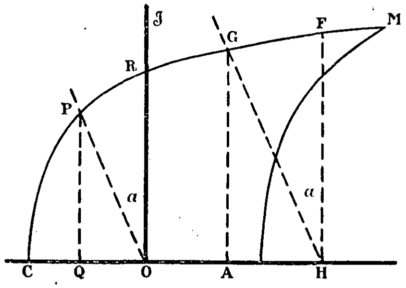

FIG. 10.—Construction for Demagnetizing Coefficient.

long bar or for a ring, that is to say, as determined under such conditions that self-demagnetizing actions are absent. Suppose that the applied magnetizing forces have been carried to a certain maximum, and then lowered so as to have the value indicated in the diagram by the length O H, and that, following the curve from the highest point M to the point F, the intrinsic magnetization I has fallen to the value H F. It is desired to learn how much further it will fall in consequence of self-demagnetizing influence. To ascertain this, draw from H a line H G, meeting the curve at G, making an angle G H F or α, such that tan α is numerically equal[*] to the demagnetizing coefficient. (For example, if the magnet has a dimension-ratio of 12, reference to Fig. 7, p. 92, shows that its demagnetization coefficient will be 0·15; and the angle whose tangent is 0·15 is about 8½ degrees). Then the length G A is the corrected value of I; for it is the value of I which corresponds to a

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[*] This is on the assumption that I and **H** are plotted to equal scales. But usually a much wider scale is adopted for **H**. Hence the plotted angle will be such that its tangent is equal to the numerical value of the demagnetization coefficient multiplied by the ratio of the scales used for I and **H**.

magnetizing force equal to the difference between the applied magnetizing force O H and the demagnetizing force A H. Now apply this construction to the case where the whole of the impressed magnetizing force has been removed. If demagnetizing influences were absent, the value of I_{rem} would be denoted by the line O R. But drawing the line O S making the angle α with O R, we obtain T S as the corrected value of the remanent magnetization.

An example of the use of Ascoli's construction is afforded by the next diagram, Fig. 11, where the steel is assumed to be Remy's tungsten steel, as used for magnets, with I_{rem} of 808 and a coercive force of 63. Draw through the value $I = 1000$ a horizontal line, and mark on it the points that correspond to values of H equal successively to -50, -100, and -150. The sloping dotted lines joining these points to the origin will then correspond to the successive demagnetization coefficients of 0·05, 0·10, and 0·15. The first of these sloping lines corresponds to a dimension-ratio (see p. 92 above) of about 25. If, therefore, we were to make of this steel a bar magnet 25 diameters long, its intrinsic remanent magnetization would not be $I_{rem} = 808$, but it would, by reason of the self-demagnetizing of the bar, fall to the point P, where the first sloping line crosses the curve, that is, to about $I = 640$. Similarly, a shorter bar that was only 12 diameters long, having (see p. 92) a demagnetizing coefficient of about 0·15, would only retain an intrinsic magnetization of about $I = 360$.

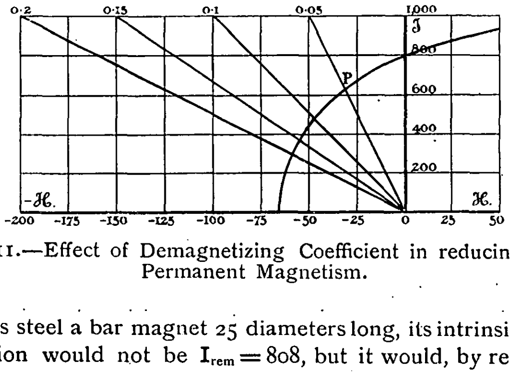

FIG. 11.—Effect of Demagnetizing Coefficient in reducing the Permanent Magnetism.

The influence of the dimension-ratio upon the magnetism of bar magnets is shown by some experiments of the late Professor Thomas Gray. Using a glass-hard charcoal steel, he found the amount of the remanent magnetization to increase regularly as the dimension-ratio of the bars was increased, as follows :—

Dimension-ratio	10	16	20	31	44	50	73	105
Remanent Magnetization ...	216	256	288	312	344	376	512	528

The values of I_{rem} do not approach the figure of 800, this being a carbon steel; and it appears that the magnet that was only 10 diameters long had a magnetization less than half as intense as that of a magnet that was 105 diameters long, though both had been subjected to equally powerful magnetizing forces. The self-demagnetizing action of the short bar is very evident.

Two other examples of the dependence of the remanent magnetism upon the dimension-ratio of the magnet may be cited from the researches of Mme. Curie :—

CARBON STEEL (0·84 % CARBON. QUENCHED AT 770° C. $H_c = 53$).

Dimension-ratio	20	22	71	Infinity (ring)
Remanent Magnetization ...	420	480	580	640

TUNGSTEN STEEL (5·5 % TUNGSTEN; 0·59 % CARBON. QUENCHED AT 770° C. $H_c = 74$).

Dimension-ratio	20	23·5	Infinity (ring)
Remanent Magnetization... ...	560	680	850

It was formerly supposed, from the researches of Scoresby, Jamin, and others, that a laminated magnet, that is, one built up of steel strips assembled together, with common pole-pieces, was more powerful than a solid magnet of equal weight and length. In old days, before the use of powerful electromagnets to magnetize the steel bars or horse-shoes, this may well have been true, provided each lamina was separately magnetized as strongly as possible before assembly. But with the modern kinds of homogeneous fine-grained steels now available, and with modern processes of magnetization, this alleged superiority of laminated magnets is illusory. Moreover, Ascoli has shown that bundles of wires or of strips possess the same self-demagnetizing coefficient as do solid magnets of the same form and size.

HEAT-TREATMENT.

We will now enter upon the question of the requisite treatment which the magnet must receive in the furnace, and in the quenching bath, if it is to yield the best performance. But this is only part of a much bigger subject, the alterations which steels undergo in their physical properties when raised or lowered in temperature.

It is found that when any kind of steel is steadily heated, or cooled, the rise or fall of its temperature is not uniformly continuous, but that there are certain pauses or points of arrest, during which the temperature of the material remains temporarily unchanged. Fig. 12* indicates the general nature of these pauses. If observations of the temperature

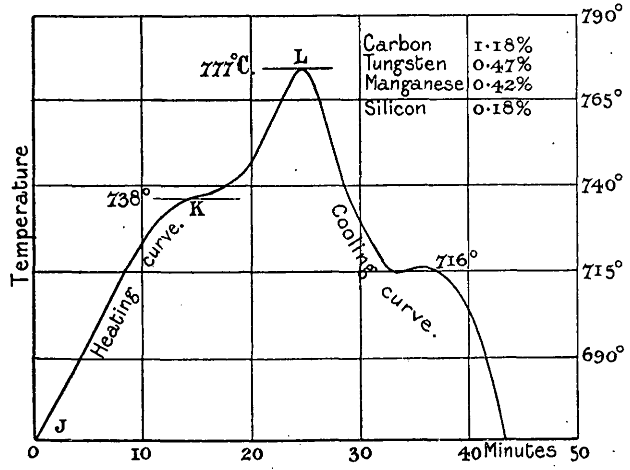

FIG. 12.—Heating and Cooling Curve.

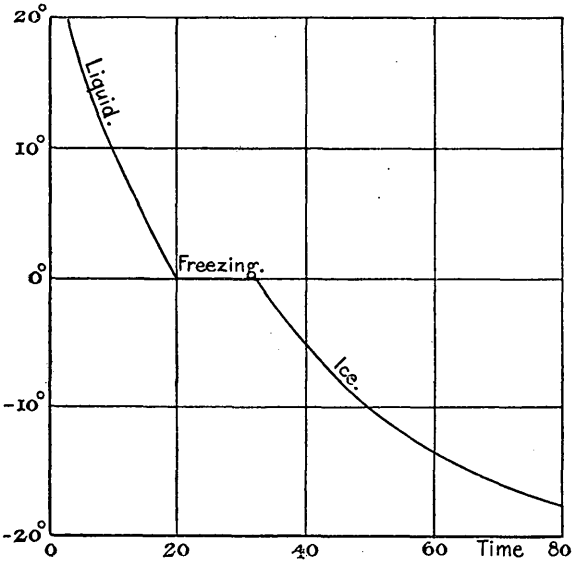

FIG. 13.—Cooling Curve of Water.

are made every few minutes, and plotted as a curve, or if continuous observations are made with an electric recording pyrometer, the curves

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[*] Fig. 12 is taken from the researches of Mr. S. Neave Brayshaw. Figs. 13, 14, and 16 are taken from Mr. J. W. Mellor's book *The Crystallization of Iron and Steel* (1905).

are found to exhibit these pauses, sometimes more than one, during heating or during cooling. For example, a high-carbon steel containing 1·2 per cent of carbon will show a pause when the rising temperature reaches about 730° C., after which it goes on ascending; and another pause during cooling when it has fallen to about 690° C. The low-tungsten steel of Fig. 12, containing also about 1·18 of carbon, has the rising pause at 738°, and the pause during cooling at about 716°. Similar peculiarities are noticed in the curves which depict the behaviour of some other substances; as, for instance, the curve of the cooling of water when it freezes into ice (Fig. 13). Here, in cooling water by a freezing mixture, down to —20° C., the pause occurs at 0°,

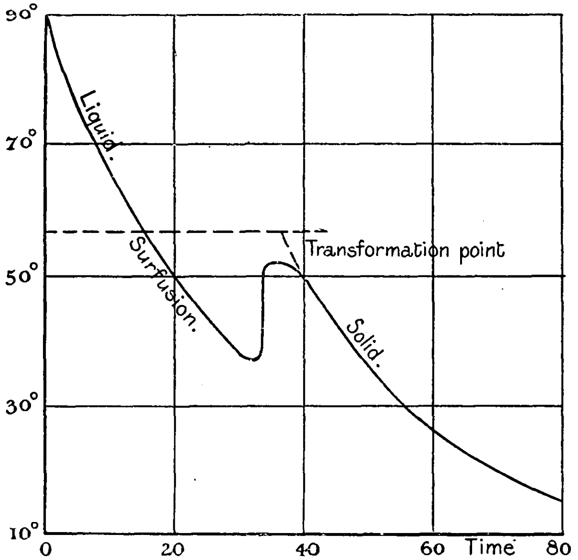

FIG. 14.—Cooling Curve showing Solidification after Surfusion.

that is, at the temperature when it freezes. The arrest of the fall of temperature until solidification is complete is a very well-known fact; and the pause indicates that at this temperature the physical change or transition from liquid to solid takes place. The latent heat of liquidity of the water is given up as it solidifies, and during the period in which that latent heat is being given up the temperature cannot fall. Suppose we take some crystals of common "hypo"—that is, sodium thiosulphate —and melt them in a flask. They melt at about 56° C. Let the molten liquid be heated up 20° or 30° higher and then left to cool, and let observations be taken of the falling temperature. A curious result follows. The substance is one which exhibits the phenomenon of surfusion. It remains liquid even when cooled a few degrees below its proper freezing-point, which is 56° C., and may even be cooled down to 25° C., or 20° C., without solidifying. But if it is then caused to solidify by contact with a minute scrap of crystal or "hypo," it begins to solidify, and the temperature at once rises to about 56° C.; after which solidification the fall of temperature is resumed. Here, again, the pause and the kink of recovery, which the curve (Fig. 14) shows, indicate a definite transition or change of physical state; the transition being in this case accompanied by such a liberation of latent heat that there is not merely a pause but an actual transient rise of temperature. Now this phenomenon can be paralleled in the behaviour of steel. It was discovered in 1873, by Barrett, that if a bright red-hot piece of steel (such as an old file) is watched during its cooling, when it has cooled down to a deep red colour it suddenly shines up again more brightly, as if it had been heated up from within; as is indeed the fact. It undergoes a transformation of some physical sort, accompanied by a liberation of latent heat which actually makes the temperature rise again. The phenomenon is known as "recalescence." It can best be shown by stretching a piece of piano-wire across a room, and heating it by passing an electric current through it until it is brightly red-hot. On switching off the current it cools, and when it reaches the temperature of transition it recalesces; and the momentary rise of temperature can be seen not only by its increased brightness of glow, but by the expansion which occurs, making the wire momentarily sag.

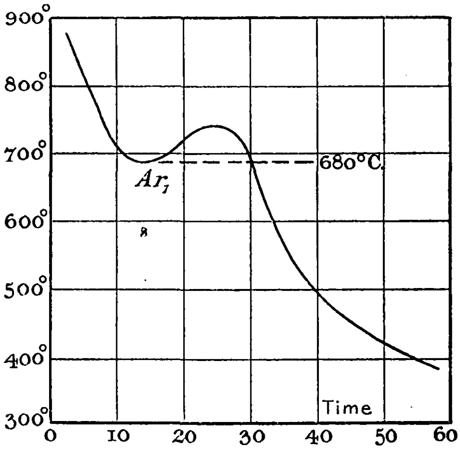

FIG. 15.—Cooling Curve of Steel, showing Recalescence (Roberts-Austen).

The cooling curve of certain kinds of steel shows clearly* the

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* Apparatus for observing and recording such cooling curves was originally devised by Le Chatelier and by Roberts-Austen, as described in the first Report of the Alloys Research Committee in 1891. More distinct results are sometimes obtained by adopting a differential method, and by recording in the curves, not the fall of temperature through a given time, but the time taken to produce a fall of one degree. The

occurrence of recalescence. For, as in Fig. 15, the temperature falls below that of the transition period (680° C.), then rises about 60 degrees, and again falls.

Now see what is found with pure iron. At a temperature of 1700° or 1800° C. it is liquid, but when it cools to about 1600° it freezes solid; and during solidification there is a large pause in the fall of temperature. Then the cooling curve falls steadily until a point, marked Ar_3 in Fig. 16, is reached, when again there is a pause at about 860°; and another pause,* marked Ar_2, occurs at about 750°.

These pauses unquestionably mark the transition of the steel from one physical state to another, heat being absorbed or evolved during the change of state. It was held by Osmond, and with some modification is held by other metallurgists, that they mark the transformation of the iron in the steel from one of its phases or states to another. Thus, during heating, alpha-iron on reaching Ac_1 absorbs some heat and is transformed to beta-iron; and beta-iron on reaching Ac_2 is transformed to gamma-iron; and the reverse transformations occur during cooling. It will be noted that always, and for every specimen, the corresponding

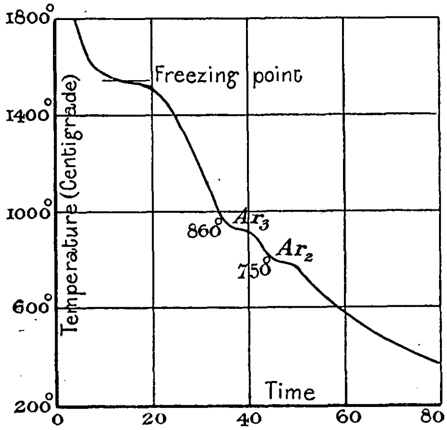

FIG. 16.—Cooling Curve showing Transformation Points of Pure Iron.

whole question of the recording of recalescence curves, and in particular of such inverse curves, is admirably expounded by Rosenhain in the *Proceedings of the Physical Society*, vol. 21, p. 180, 1907–9.

* The notation is due to Tschernoff and Osmond. There are, in general, three transition points, or points of arrest, in any heating or cooling curve of steel. Those on a heating curve are marked *Ac*, the *c* indicating *chauffement*. Those on a cooling curve are marked *Ar*, the *r* standing for *refroidissement*. The lowest number is the lowest temperature. Thus Ar_3 means the highest of the three transition temperatures on a cooling curve. They are usually not very sharply defined, being ranges of temperature rather than points; and they differ in different brands. For instance, Ar_3, which for pure iron is at about 860°, is in a mild steel lower. In a 0·02 per cent carbon steel Ar_3 begins at about 840° and extends to about 800°. In a 1 per cent carbon steel Ar_3 occurs at about 710° or 720°, when it is difficult to distinguish from Ar_2 and Ar_1, and the point is then denoted as Ar_{321}.

transition points are a little higher on the heating curve than on the cooling curve. Thus, for the low-tungsten high-carbon steel shown in Fig. 12, Ac_1 is at about 738°, and Ar_1 at 716°. Also, generally, any increase in the percentage of carbon lowers the transition points, and the presence of other elements—manganese, chromium, silicon, etc. —affects them. The non-magnetic gamma-iron, which in pure iron exists stably only at temperatures over 860°, will, when carbon is present, exist stably to a lower temperature. In a 0·3 per cent carbon steel the gamma-iron will persist stably down to about 780° or 740°, when it changes to alpha-iron (or to beta-iron and then to alpha-iron), evolving heat and causing the recalescence. In a 0·6 per cent steel the change occurs at 735° to 705°. In a 1·2 per cent carbon steel the gamma-iron is transformed straight to alpha-iron at about 690°. These things are summarized diagrammatically in Fig. 17.

For us the most important fact of all is that when any specimen has cooled down through the recalescence stage it is capable of being magnetized. A steel, if of such a composition that it can harden, hardens if quenched at a temperature above recalescence. If it is cooled slowly through the recalescence stage and quenched at a lower temperature it is not thereby hardened, or only hardened imperfectly. And as the coercive force of magnets is bound up with their being properly hardened, it is imperative for magnets which are to have the greatest coercive force that they shall be quenched at a temperature above that at which they recalesce; that is to say, they must be quenched at a temperature such that the iron in them is still in the non-magnetic or gamma state. And they must be quenched *quickly*.

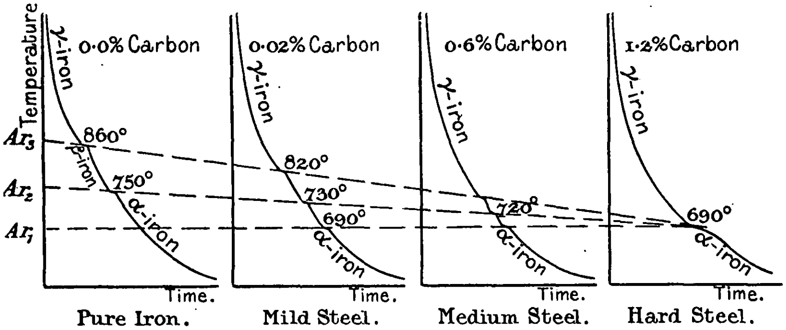

FIG. 17.—Cooling Curves for Steels of Different Composition (after J. W. Mellor).

Now this raises the much-disputed question as to the reason why steel becomes hard when quenched. An old and fantastic idea, which we may at once dismiss, was that some of the carbon solidified as minute diamonds. Another suggestion is that in the sudden cooling the hard gamma-iron has not time to transform itself into alpha-iron, and remains fixed. Another is that the constituent hardenite, an alloy containing about 0·9 of 1 per cent of carbon (which if cooled slowly has time to transform itself into pearlite), is arrested and remains excessively hard. On this view hardenite is in quenched steels the hard matrix which holds together the crystals of ferrite, if the steel has less than 0·9 per cent of carbon, or the crystals of cementite, if the steel has more than 0·9 per cent of carbon. No final view has yet found acceptance. But why should the hardening by sudden quenching confer the power of magnetic retentivity? Apparently the gamma-iron and all the several constituents, whether called ferrite, austenite, martensite, sorbite, hardenite, or cementite, are non-magnetizable at temperatures above the recalescence point. Apparently also, from the recent researches of Dr. S. W. J. Smith, cementite is non-magnetic* at temperatures above 210° C. Why should the quenching, which presumably arrests the transformations that some of these constituents would otherwise undergo in cooling, render them capable of retaining magnetism? It cannot be said that any satisfactory answer† has yet

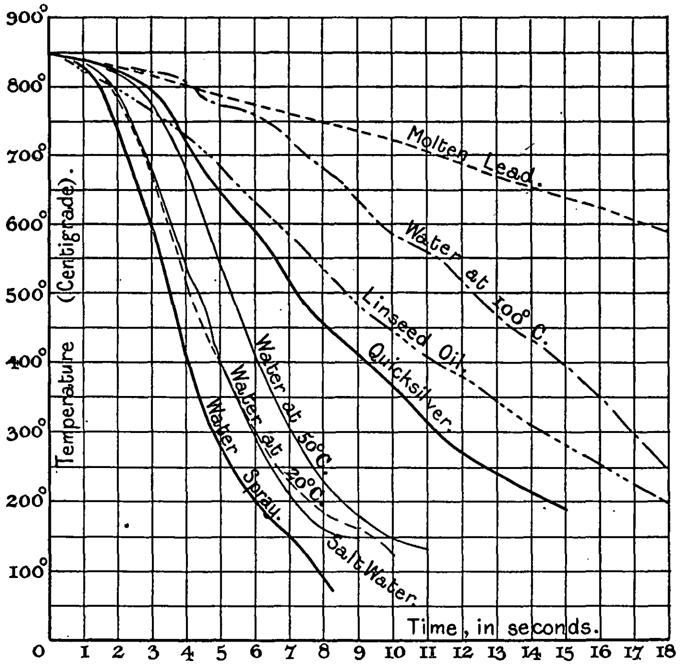

FIG. 18.—Quenching Curves (adapted from Le Chatelier).

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* This is perhaps the reason why magnet-makers consider that those carbon steels which make the best permanent magnets contain less than 0·9 per cent of carbon.

† In a paper published after the delivery of this lecture, Dr. S. W. J. Smith suggests that ferrite contributes nothing, or less than nothing, to the *permanent* magnetism.

been given. According to the modern view, the act of magnetization in iron or steel consists in the production of molecular arrangements, in which the magnetic molecules, whatever they be, are brought into alignment with the magnetizing forces. This is the theory of Weber as modified by Ewing, and of its general truth there can be no doubt. But this at once raises the question: Why quenching confers on the steel the greater power to retain the aligned rows or groups of magnetic molecules in position, and to prevent them from instantly returning into a miscellaneous disposition when the magnetizing forces that have constrained them into alignment have been removed? One thing emerges from the conflicting theories: that sudden cooling of the steel, at whatever stage, tends to conserve whatever composition, structure, or state, the substance possessed at that temperature, and which it would have lost if it had cooled slowly. Bearing this in mind, it will be evident that rapidity of cooling is as important as the right temperature. We must cool the steel, but how quickly, and to what degree? It is obvious that if we plunge a brightly red-hot bar into ice-cold water it will be chilled more rapidly than if we plunged it into hot water, or boiling oil, or molten lead. But if we apply a water-spray at, say, 20° C., it will chill the bar quicker than plunging it into water at 0° C. Some kinds of steel will not withstand a quenching in ice-cold water, but split or crack. Thin bars which present more surface, relatively to their solid contents, than thick ones, are more rapidly chilled than thick ones, though both are dipped into the same brine. Tool-makers and magnet-makers have their own procedures, the results of experience; but some of the recipes they follow are quite absurd. There is no advantage in adding to the water in the quenching tank, stale beer or other organic liquids. By means of his hardness testing-machine Brinell found the quenching of a 0·1 per cent mild steel, having previously a hardness of 99 on the Brinell scale,* to produce the following hardnesses with the cooling agents named:—

	Temperature of Bath.	Hardness.
	° C.	
Molten lead	350	112
Boiling water	100	118
Wood tar...	80	121
Cold water	20	149
Brine	20	156
Soda solution	20	202

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* Stead gives following values of the Brinell scale of hardness: Purest Swedish iron, 87; rail steels, 200 to 210; Clarence pig-iron, 104 to 160; grey mottled, 153; white iron, 418; hardened steel file, 560. The Brinell testing machine is manufactured by Messrs. J. W. Jackman & Co., of London and Manchester.

The curves of Fig. 18, which are adapted from data given by Le Chatelier, show the rapidity of cooling with the different agents named on the curves. A water-spray is the most efficient. Recently Messrs. James G. Gray and A. Ross have used liquid air to produce extremely rapid cooling. The one really important thing, however, is to make certain that the steel before quenching has been heated up above Ac_3, that it is still above Ar_3 when quenching is applied, and that it is entirely cooled in the interior below Ar_{321} before quenching is stopped. *It must pass as rapidly as possible through the recalescence point*; all else is relatively unimportant. An example will suffice. Mme. Curie took a bar about 20 diameters long, of a 0·84 per cent steel, which when annealed showed feeble retention of magnetism, $\mathbf{I}_{rem}$ being only 85 and $\mathbf{H}_c$ only 8. This steel must be heated up to 730° (the value of Ac_3) to reach the transformation point; and it recalesces at 680° (which is Ar_{321}), on cooling. Now this bar was heated up to 705° and quenched in cold water, and then magnetized and tested. It was then heated up to 770° and quenched, and again magnetized and tested. In the first case it had never reached the transformation point, and was not, when being quenched at 705°, in the non-magnetic state. Whereas in the second case it had been heated up till transformed into the non-magnetic state, and was still in the non-magnetic state at 770° when quenching was applied. The following were the results :—

	$\mathbf{I}_{rem}$.	$\mathbf{H}_c$.
Annealed	85	8
Quenched, in the magnetic state, at 705° ...	130	14
Quenched, in the non-magnetic state, at 770° ...	410	52

The same bar was again heated up to 800°, and allowed to cool slowly in air until its temperature fell to 690°, when it was quenched, with the result that $\mathbf{I}_{rem}$ was 380, and $\mathbf{H}_c$ 50; little inferior to the preceding case. Here the quenching was only just at the temperature of recalescence. There could be no clearer proof of the absolute dependence of the coercive force upon the quenching being so conducted as to carry the steel quickly through the recalescence stage. Now the file-makers are quite familiar with recalescence, and know that the file will not harden properly in the quenching bath until it is first heated above the temperature of recalescence. A very good instruction for quenching magnets would be to say to the practical workman : heat and quench as you would for a file. And it is a rule with the workman that "quenching at the lowest temperature at which it will harden produces the strongest and toughest tool." * Mr. Brayshaw has re-

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* B. E. Jones. See also V. A. Stobie, *Journal of the Institution of Electrical Engineers*, vol. 42, p. 675, 1909. But this is not necessarily true of high-tungsten steels.

marked that in the hardening both of tool steels and of magnet steels there is a great difference between the hardening that is *good* and the hardening which is *best*.

Here the point arises whether there is any advantage in heating up the steel, prior to quenching, to a considerably higher temperature than Ac_3. And this raises the whole question of the prior heat-treatment of the steel. In the processes, whether of rolling, drawing, or forging, by which the magnet is brought to the desired form, the steel is mechanically altered in its structure. Its crystalline grains are dragged over one another and deformed. Steel that has in this way been "worked" differs from a mere steel that has been cast; it is no longer homogeneous. Hence it is important to "normalize" the steel by a preliminary slow heating up to 850°, or 900^c (or even higher), and after being kept at this height for a few minutes, cool in air to recrystallize the substance with a fine grain.

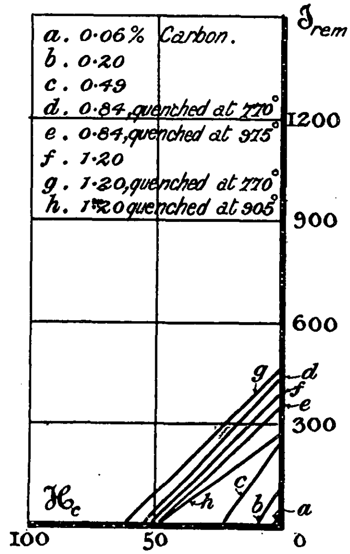

Fig. 19.—Diagram of Carbon Steels. Researches of Mme. Curie.

Mme. Curie has examined the effect on the magnetic properties of the temperature to which the hot steel is carried before being quenched. The results for carbon steels are graphically shown * in Fig. 19. It will be noticed how useless the low-carbon steels are. The 0·84 per cent carbon steel, with I_{rem} 426, and H_c 53, when quenched at 770°, showed distinctly worse properties if quenched at 975°; the remanence falling to 358 and the coercive force to 48. The best result was the 1·20 per cent carbon steel, hardened at 770°, giving a remanence of 460 and coercive force 60. But this steel when heated to 905° degenerated, giving a remanence of only 264, and a coercive force of only 48. So far as carbon steels are concerned therefore, it appears that it is a distinct disadvantage to quench at temperatures greatly above the recalescence point. Mme. Curie also tried the effect of a cyclic variation between temperatures a little above and a little below that of recalescence. Any specimen carried through such a cycle undergoes two transformations. She found that for the high-carbon steels the effect of carrying the specimen one or

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* In Mme. Curie's memoir no curves are given for these steels, only statistics of numbers. In Fig. 19 these numbers are plotted on the axes, and simply joined by straight lines, without attempting to reconstruct the curves. So also in Fig. 21, to the same scale, for the magnet steels for which Mme. Curie gives the curves.

more times through such cycles is generally to improve the quality, and, in fact, may repair the deterioration produced by overheating.

Gumlich has recently shown that in carbon steels having more than about 0·6 per cent of carbon, the coercive force on hardening at 800° is greater than that after hardening at 900° or at 1100°.

Recently Messrs. J. G. Gray and A. Ross have given some data of a Whitworth tungsten steel, of composition 4·01 per cent tungsten, 0·51 carbon, 0·13 manganese, 0·19 silicon, of which a rod 111 diameters long was magnetized in a field of $\mathbf{H} = 150$. Annealed from 900° it showed a remanence of 540 and a coercive force of 10 only. If reheated to 900° and quenched at 450°, the respective values became 570 and 7·5. But reheated and quenched at 980° the remanence rose to 610 and the coercive force to 37.

In none of the preceding examples were the specimens tempered: they were all in the hardened state as they came from the quenching bath. But since many magnet-makers temper their magnets after hardening them, some consideration of this process is necessary.

TEMPERING.

Tempering is a well-known term meaning softening* the steel by a more or less gentle reheating. The workmen in the steel industries are accustomed to judge of the degree to which a steel has been

TEMPERING OF STEELS.

Deg. C.	Tint of Film.	Service.
220°	Pale straw	Short bar magnets, lancets
230°	Straw	Razors and tools for turning cast iron
240°	Yellow	Tools for turning wrought iron, penknives, short compass-needles
260°	Orange	Long bar magnets, cold chisels, planes, gauges, hatchets, drills
270°	Orange to purple	Chipping tools, tools for turning brass
280°	Purple	Strong springs, sword blades
300°	Blue	Compass needles, watch-springs, fret-saws
320°	Pale blue	Large saws

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* "The use of the word *temper* by translators, and persons more or less remotely connected with the usages of the steel trade, to denote a change brought about by quenching from a high temperature, which every craftsman calls *hardening*, leads to confusion, and should be abandoned entirely."—H. Brearley, *The Heat Treatment of Tool Steel*, 1911, p. 9.

The following quotation from p. 26 of *The Nomenclature of Metallography*, officially issued in 1902 by the Iron and Steel Institute, is authoritative :—

"TEMPERING.—(Regulating ; hence, in the special case of modifying the maximum hardness of steel, *rendering softer*.) The act of partially or wholly undoing what has been previously done by 'hardening.' Tempering must be preceded by 'hardening.' The term 'oil-tempering' [meaning quenching in oil] which has obtained some currency, should be 'oil-hardening,' as the result of the process referred to is to harden, whereas to temper is to withdraw or modify previously conferred hardness."

softened or let down in temper by the tint which it assumes on the surface in consequence of the formation of a film of oxide. The following table states briefly the chief services for steels of different tempers, and the temperatures to which the steel must be reheated to attain the respective tints. There is some indefiniteness about the matter, because a higher temperature applied for a short time will confer the same tint as a lower temperature for a longer time. Thus a razor-blade heated at 230° C. for 20 minutes acquires a straw tint; and a saw-blade (itself of a lower-carbon steel) if heated in a muffle at 320°, will in two or three minutes turn straw-colour; and, if the heating is prolonged, will then turn yellow, then orange, then purple, and finally blue.* If heated to 400° C. (just under a red heat) all the colour goes, the steel being then annealed soft.

The question of there being any advantage in tempering bar magnets was investigated over twenty years ago by Barus and Strouhal.† They used wires of "English silver steel," ‡ which were very carefully selected, and from which were cut a number of rods of different lengths so as to have different dimension-ratios, varying from 10 diameters long to 50, or in some cases 120 diameters long. The specimens were first heated bright red hot and quenched with cold water so as to be all glass-hard. They were then systematically tempered by heating in steam at 100° for an hour, then for 2 more, 3 more, and 4 more hours; then in aniline vapour at 185° for 20 minutes, 40 minutes, 2 hours, 4 hours, 6 hours; then in a molten lead bath at 330° for 1 minute, then for 1 hour; also in molten zinc at 420°; finally annealed by heating to visible redness and slow cooling. Between each successive stage measurements were made on their hardness and on their specific magnetism, that is, on the amount of magnetic moment per unit of mass, which they retained after being well magnetized. The table on page 109 gives a brief summary of only one series of these elaborate experiments.

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* The following quaint instructions for the fashioning of compass-needles are taken from the *Magneticall Advertisements* of William Barlow, printed in 1616. "The substance in any wise ought to bee pure steele, and not iron. For most assuredly steele will take at least tenne times more vertue then iron can doe, but especially if it hath his right temper. And that is this: Heat it in the fire untill it be past red hot, that it be whitish hot, and quench it in cold water suddenly: So is it brickle in a manner as glasse it selfe, and is at that time incapable of the vertue of the *Loadstone*. Then must you, laying it upon a plaine table, warily rubbe with fine sand all the blacke cullour from it, if before you put it in the fire, you annoynt it with soape, it will scale white of it selfe, then heat a barre of iron well neare red hot, and holding one end of the needle with a small paire of tongs, lay the other end upon the hot barre, and presently you shall see that end turne from a white to a yellowish, and after to a blewish cullour, then take that end with your tongs, and doe the like unto the other, thrusting it forward upon the barre until the cullour of the whole needle become blewish: then throw it on a table, and let coole of it selfe: and so is he of the excellentest temper, and most capable to receive the greatest power from the Magnet" (p. 67).

† *The Electrical and Magnetic Properties of the Iron Carburets*, by Carl Barus and Vincent Strouhal. Washington (United States Geological Survey), 1885.

‡ A carbon steel containing from 1 to about 1·25 per cent of carbon, and very carefully melted in the crucible so as to have a fine grain with a silvery fracture. Formerly it was supposed to have a trace of silver in it; but analysis has never shown any.

In Fig. 20 the results are plotted out. One fact leaps at once into view: that, whether the steel be hard or soft, long bar magnets retain a higher magnetization than short ones. A glass-hard bar 50 diameters long retained twice as much as one 10 diameters long; and a perfectly soft bar 50 diameters long retained ten times as much as one 10 diameters long. This table gives no values for the coercive forces, and does not state with what degree of fixidity these values were held.

State of Temper.	Hardness.	Mean Remanent Magnetization, I_{rem}.				
		$\delta = 10$	$\delta = 20$	$\delta = 30$	$\delta = 40$	$\delta = 50$
Glass-hard ...	45·7	188·0	300·8	348·8	372·0	386·4
Straw tint ...	26·3	172·2	321·6	396·2	430·4	452·0
Blue tint ...	20·5	154·4	366·4	536·0	643·2	698·4
Annealed soft ...	15·9	35·4	89·6	164·0	254·4	356·8

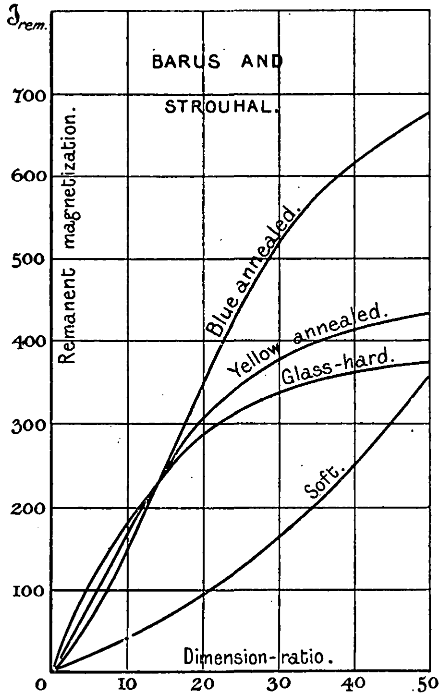

FIG. 20.—Result of Tempering Carbon Steel (Barus and Strouhal).

Another inference from the table is that for short bars, a glass-hard state is the best, since each successive degree of tempering lowered the remanent magnetization. For the long bars, 50 diameters long, it appeared that while I_{rem} had the value 386 for the glass-hard state, the value rose to 452 in the straw-tint temper, and to 698 in the blue temper. Clearly, tempering had raised the susceptibility of the steel; but this does not prove the blue temper to be superior, since it tells us nothing about the fixidity. It is certain that in the blue temper the coercive force must have been less than in the straw temper or in the glass-hard state.

So far, as regards carbon steel. But when we turn to the alloy steels we find the facts to be no less significant. On this topic no researches are more important than those of Mme. Curie.

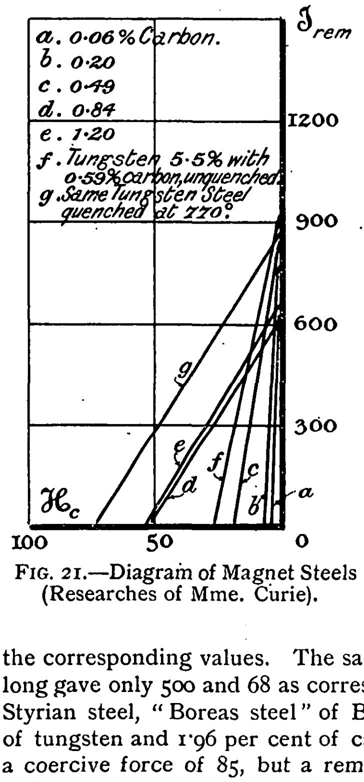

FIG. 21.—Diagram of Magnet Steels (Researches of Mme. Curie).

Fig. 21 gives the results for five carbon steels and for one quality of tungsten steel, namely, Allevard, having 5·5 per cent of tungsten, and 0·59 per cent of carbon. The two curves for high-carbon steel (0·84 and 1·2 per cent of carbon respectively) are about as good as can be found for any carbon steel, giving I_{rem} as 670 and 645, and H_c as 58 and 53 respectively. These high values relate to specimens formed as rings, for which the dimension-ratio is therefore infinite. The Allevard steel not quenched gave I_{rem} 900 and H_c only 26; but when quenched at 770° C. it gave I_{rem} 850 and H_c 73. Another ring of tungsten steel from Assailly, containing 2·7 per cent of tungsten and 0·76 of carbon, gave 800 and 69 as the corresponding values. The same steel as a bar about 20 diameters long gave only 500 and 68 as corresponding values. A very hard special Styrian steel, "Boreas steel" of Böhler Bros., containing 7·7 per cent of tungsten and 1·96 per cent of carbon, quenched at 800° C., showed a coercive force of 85, but a remanence of only 370, in a bar about 20 diameters long. This steel is a self-hardening tool steel, very difficult to work. For short bar magnets it would surpass all other tungsten steels.

Mme. Curie also examined a molybdenum steel, having 3½ to 4 per cent of molybdenum, and from 1·25 to 1·72 of carbon. That with 1·25 surpassed even Boreas steel, as it gave H_c of 85 with I_{rem} of 530 even in a bar only about 20 diameters long. The brand having

1·72 of carbon quenched at 745° gave $H_c = 73$, $I_{rem} = 465$. If quenched at higher temperatures the values of the coercive force increased slightly, while those of the remanent magnetization fell considerably.

In view of these remarkable facts, and the widespread recognition given to the value of the tungsten steels, it seems important to add an epitome of our present knowledge concerning tungsten steels in general, and their properties as dependent on heat-treatment. It appears that those tungsten steels that have been found good for magnets fall under two groups: (1) those containing from 5½ to 7 or 8 per cent of tungsten with about 0·5 per cent of carbon, and (2) those containing 2½ to 3½ per cent of tungsten with about 1 per cent of carbon. Those with the higher proportion of tungsten are of course dearer. The preference shown to high-tungsten low-carbon steels over the lower-tungsten higher-carbon steels may be due to the circumstance that the former are somewhat more easy to work. There are, of course, tungsten steels with other proportions. It will be convenient to regard those of the second group as medium tungsten steels.

The standard source of information on the composition and properties of tungsten steels is the well-known paper of Sir Robert Hadfield, in the *Journal of the Iron and Steel Institute* for 1903, pp. 14–118. From this paper it appears that metallurgists hold that tungsten does not *of itself* harden iron; but that it helps to prevent such carbon as is present from segregating (as it would in a very high-carbon steel) as graphite, or (as it would do in a moderately high-carbon steel) from separating itself as carbide of iron (cementite), and to maintain it in the condition of hardening carbon—that is, as either a solution of cementite in hardenite, or perhaps as a sub-carbide of iron. Certainly the presence of tungsten tends to prevent the formation of large crystals, and to promote the retention of a very fine grain with a silky fracture. Chromium also tends to maintain carbon in the hardening condition, and probably manganese and vanadium act similarly. All these metals tend of themselves to lower the magnetic permeability of the steel, but tungsten in a moderate percentage does so to a less extent than do chromium, nickel, or manganese. If Mushet steel is heated to about 850° and cooled slowly, a marked recalescence occurs at about 660°. High-tungsten steels, such as Mushet's, can be softened by heating to a temperature below redness and then quenching in water. Steels, generally, soften by being annealed at a temperature immediately below that of the point at which their transformation point during heating (Ac_{123}) occurs. The addition of tungsten may produce a steel which has its recalescence point actually below visible red, and such a steel is self-hardening in air without being quenched in cold water. Osmond remarks of Hadfield's tungsten steels that they show three distinct cases of heat behaviour. (1) If not heated above 850° they show cooling curves similar to those of carbon steels with the same carbon content. (2) If heated to 1040°, the higher transformation points Ar_3 and Ar_2 are not altered, but Ar_1 is lowered

(3) If heated to 1300° the transformation points Ar_3 and Ar_2 are also lowered and tend to rejoin Ar_1. There follows this significant if paradoxical result, that quenching a tungsten steel at 600° will yield soft, medium-hard, or very hard product according to the temperature of immediate previous heating. Dumas, commenting on this, suggests that prolonged heating to the higher temperatures tends to separate a double carbide of iron and tungsten, while double carbide is not dissociated at 850°. Osmond has made observations on Allevard steel, which may be summarized thus :—

Temperature of Heating.	Transition Temperature.	Condition after Quenching.
°	° °	
920	695—685	Soft
1015	675—665	Soft
1310	505—485	Soft

Temperature of Heating	Temperature of Quenching.	Condition after Quenching.
°	°	
830	630	Mild
1020	625	Hard but filable
1310	555	Very hard

Hadfield's paper of 1903 contains cooling curves taken by Osmond from a number of specimens of tungsten steels prepared by Hadfield. From these curves Figs. 22, 23, and 24 are selected. They relate to four alloys of the following compositions :—

Mark of Alloy.	Percentage Content.			
	Tungsten.	Carbon.	Silicon.	Manganese.
"B"	0·20	0·15	0·04	0·22
"G"	1·49	0·21	0·07	0·25
"H"	3·40	0·28	0·06	0·28
"J"	8·33	0·46	0·08	0·28

The curves are constructed as differential curves in which the abscissæ are proportional to the number of seconds taken to fall through a given range of temperature. It will be seen from Fig. 22 that the steel "B," which is a low-tungsten steel, differs in no respect from that of an ordinary carbon steel, while the curves "G" and "H," which are for medium-tungsten steels, show a lowering of Ar_3 and of Ar_1. In the high-tungsten steel "J," containing 8·33 per cent of tungsten, this effect is still more strongly marked. Also the medium-tungsten steel "H," Fig. 23, when not heated above 850°, shows no lowering of the transformation points, as compared with a carbon steel of equal * carbon content. But when cooled from higher temperature it shows the lowering of Ar_1 and even of Ar_2 and Ar_3.

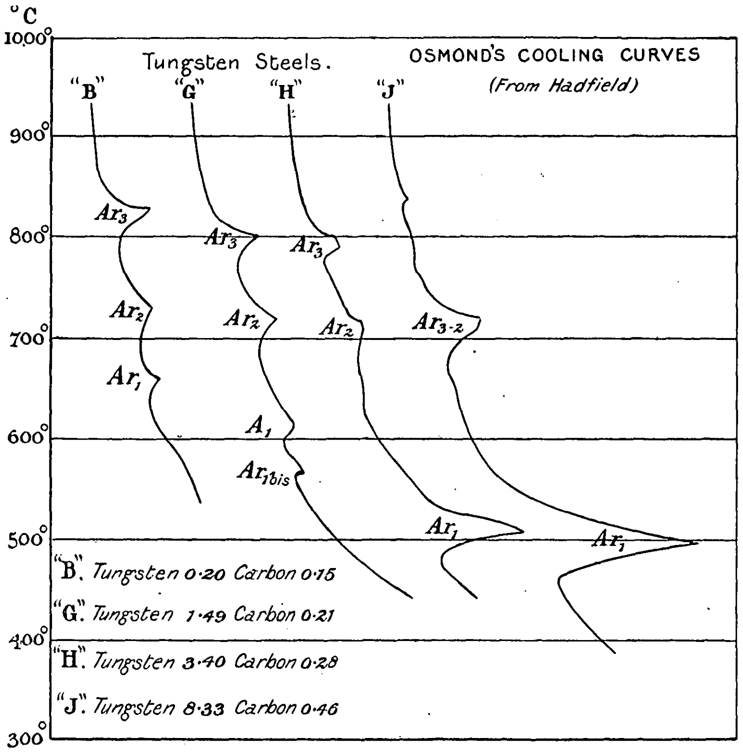

FIG. 22.

In the case of the 8·33 tungsten steel "J," the effect of raising the

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* Whether tungsten forms a double carbide in the hardening constituent is an uncertain point. Some light might be thrown on this and kindred points, if instead of stating the mere percentages present, the chemical compositions were stated in terms of the relative numbers of gram-molecules present.

temperature prior to cooling is brought out; for when not heated above 850° the recalescence point occurs at about 680°, whereas after being heated up 1040° the recalescence point is lowered to 500°, and after being heated to 1920° it is still further lowered.

From the general trend of Hadfield's observations, it would appear that the best results as regards hardening would be to choose a steel containing from 4·5 to 6·5 per cent of tungsten, from 0·4 to 1·5 per cent of carbon, from 0·2 to 0·4 of manganese; forge as cool as possible; heat to 1310° for a short time; allow to cool to 600°, then quench. In forging tungsten steels the usual rule is: heat to a yellow heat (about 1000° C.), and do not go on forging after the temperature has fallen to a medium red (about 760°).

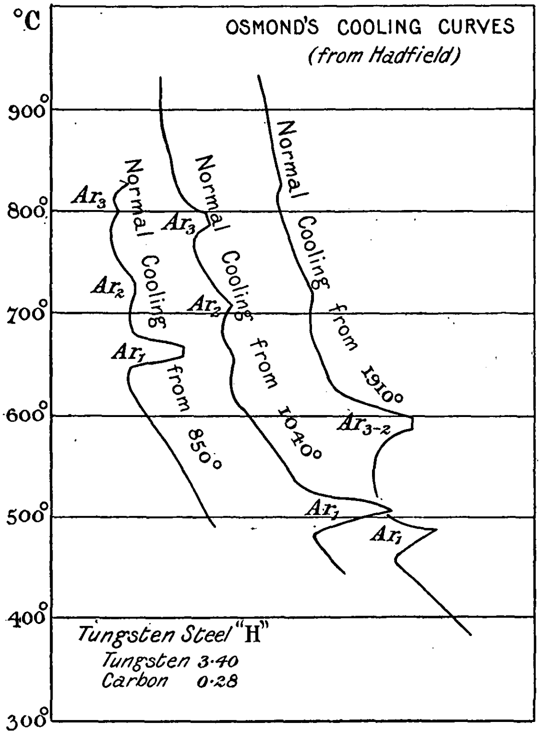

FIG. 23.

In the discussion of Hadfield's results, Barrett remarks that in the steel containing 8·33 per cent of tungsten there appears a new transition point below the usual Ar_1; that this point occurs at 530° to 490°; and that it is specifically due to tungsten.

As the result of Hadfield's researches on the alloy steels (including also the manganese steels and nickel steels), we know now of three types of material :—

1. Those for which the transformations occur at or above the temperature at which iron becomes magnetizable (soft iron and mild steels) ;
2. Those for which the transformation that confers hardness occurs at a temperature below that at which iron becomes magnetizable, but above ordinary atmospheric temperatures (high-carbon steels and the hard-alloy steels) ;

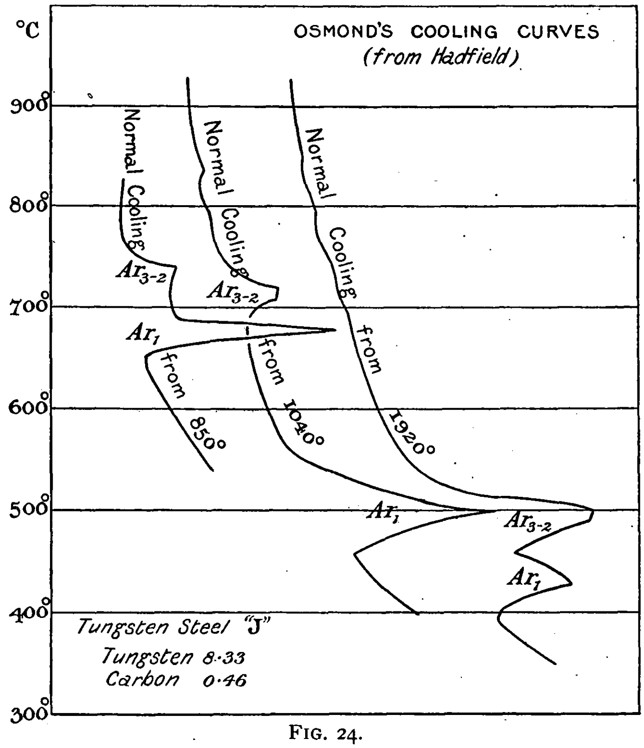

FIG. 24.

3. Those for which the transformation that confers hardness occurs below ordinary atmospheric temperatures, and which can become magnetizable (if at all) by prolonged heating and very slow cooling (Hadfield's manganese steel, and certain nickel and chrome steels).

Materials of the first type are magnetic, but are useless for permanent magnets. Materials of the third type are self-hardening, but non-magnetic. Materials of the second type are hardening, and some are self-hardening, but are magnetizable.

In a research on the stability of magnetism in 1902, Ascoli compared with Allevard steel a tungsten steel containing 4·16 per cent of tungsten and 1·15 of carbon from the steel works of Glisenti, near Brescia, and found it to be almost equally excellent, and indeed better for long magnets.

In a paper read before the Iron and Steel Institute in 1907, Mr. T. Swinden described the properties of a number of steels containing about 3 per cent of tungsten and with carbon content varying from 0·14 to 1·24. He showed that with all these steels if they are heated up to a high temperature (960° for low carbon, to 1,130° for high carbon) the temperature of recalescence is thereby lowered to about 570°.

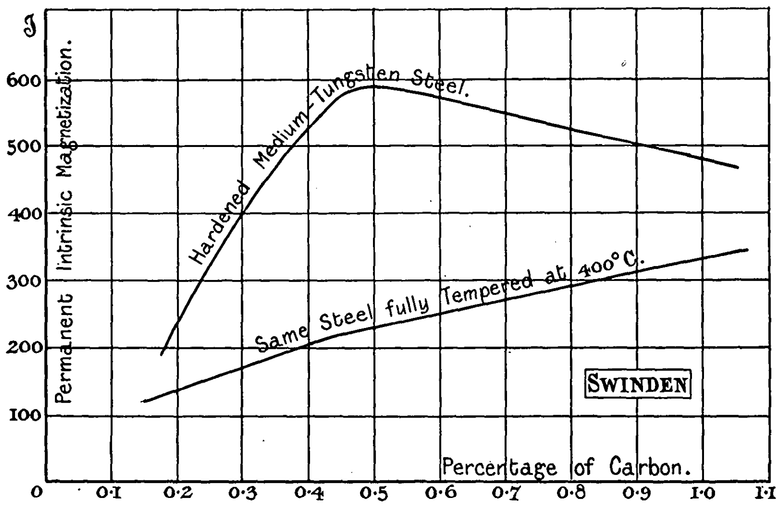

FIG. 25.—Relation between Remanence and Carbon Content in Medium-tungsten Steel.

In a second paper read to the Institution of Electrical Engineers in 1909,* Mr. T. Swinden described an investigation into the magnetic properties of this same series of medium-tungsten steels containing from 3 to 3·25 per cent of tungsten, and of carbon content from 0·144 to 1·07 per cent. He used bars having a dimension-ratio of 32. His conclusions are therefore not directly applicable to high-tungsten steels or to magnets having other dimension-ratios. His specimens were treated as follows: They were normalized by heating to 950° for 15 minutes, and cooled off in air. To harden them they were heated to 900° (changing the excess cementite cell-walls to mere specks) and then cooled to 810°, or 780°, or 760°, or 740°, according to the carbon content, and then quenched. They were tempered by three successive stages: (1) at from 60° to 75° for 14 hours; (2) at from 80° to 85° for 13 more

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* *Journal of the Institution of Electrical Engineers*, vol. 42, p. 641, 1909.

hours; (3) at 400° for 1 hour. At each stage of the process they were examined magnetically to ascertain the value of the remanence and of the coercive force. Fig. 25 shows the variation of the remanence with the carbon content, and Fig. 26 the variation of the coercive force with the carbon content,* both diagrams relating to the hardened and to the tempered steels. It will be seen that in these 3 per cent tungsten steels tempering is useless. Also the maximum remanence occurred when about 0·45 per cent of carbon was present; but the coercive force showed an increase up to the highest proportion of carbon. Had bars of greater dimension-ratio been used, for which the self-demagnetizing factor is smaller, the remanence curve for the lower percentages of carbon would have been higher, and the maximum would have occurred with a softer steel. The table on page 118 is a sample of the results upon a steel having 3·08 per cent of tungsten and 0·89 of carbon, quenched at 760°.

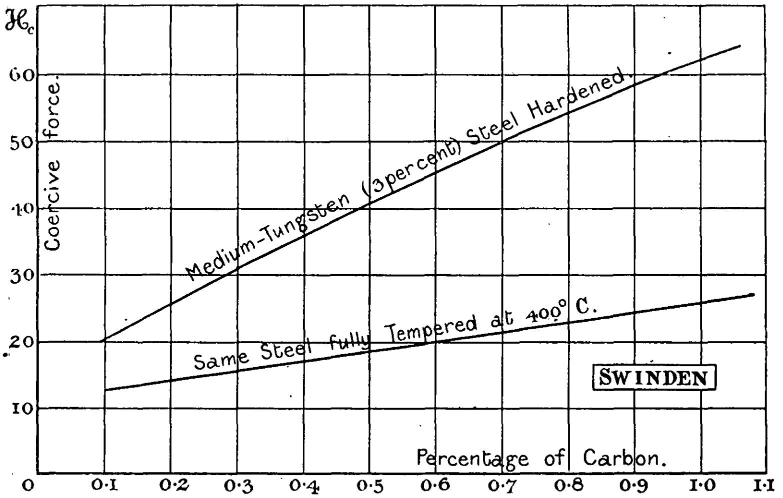

FIG. 26.—Relation between Coercive Force and Carbon Content in Medium-tungsten Steel.

In 1910 Mr. Shipley N. Brayshaw brought before the Institution of Mechanical Engineers a research on the hardening of carbon and low-tungsten tool steels. Though this paper deals only slightly with magnetic matters, it is of great importance from the thoroughness with which it handles the heat-treatment and mechanical properties of these steels. Two qualities only of steel were examined, namely, such as are used for making milling cutters: (1) a carbon steel containing from 1·14 to 1·16 per cent of carbon, with 0·37 to 0·4 of manganese; (2) a

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* Fig. 26 should be compared with Fig. 3, the corresponding diagram for pure carbon steels.

tungsten steel containing 0·47 to 0·57 of tungsten, with 1·15 to 1·16 of carbon and 0·42 to 0·57 of manganese. This low-tungsten steel recalesces in the range from 731° to 725°. The recalescence point is retarded, that is, lowered, if the steel is previously heated to 890°. The hardening point (Ac_{123}) is definite within six degrees. Brayshaw employs a bath of molten mixed chlorides of sodium and potassium in which to "soak" the steel before quenching. If heated above the recalescence point, and then soaked at a temperature between *Ac* and *Ar*, and then quenched, it is softer than if so soaked without previous heating. If raised more than twenty or thirty degrees above the recalescence point, and then quenched, the hardness is less than if quenched without being heated so high. Identical results are produced on quenching in oil from temperatures anywhere between 760° or to 940°. Heating for a short time to 810° or to 880° before quenching produces great hardness, but 30 minutes' soaking at such temperatures impairs the steel. Soaking for even 7½ minutes at 880° impairs the steel. Quenching in brine at 5° is perceptibly better than quenching in brine at 24°. The ill effect of heating for 30 minutes at 840° to 900° is scarcely improved by soaking for 30 minutes at 760°. A good result is obtained by a short soaking at 880°, followed by a lowered temperature; and best when this lower temperature is near or a little above the hardening point. Thus on a steel with 0·5 per cent tungsten, 1·15 of carbon, 0·31 manganese, and 0·21 silicon, a 10 minutes' heating at 893° followed by 30 minutes at 731° yielded a hardness of 600 (Brinell's scale), while if the lower temperature was prolonged for 120 minutes the hardness fell to 418, and after 240 minutes to 321.

	Remanence.	Coercive Force.
Quenched at 760°	584	58·8
Reheated 60–75°, 14 hours ...	583	58·6
Reheated 80–85°, 13 hours ...	582	57
Annealed 400°, 1 hour	1159	21·7

Holborn, in 1891, examined several sorts of tungsten steel to ascertain what was the most favourable temperature to which they should be heated for quenching. For Böhler's steel with 2·8 per cent of tungsten and 1·05 carbon, and for Seebohm's steel with 2·16 tungsten and 1·14 carbon, he found (for rods of dimension-ratio 11) the best temperature to be 850°. With higher temperatures the remanence was less.

At the present day tungsten steels are used by almost all magnet-makers. Messrs. H. Shaw & Sons, of Sheffield, the old-established firm which for three generations has made most of the horse-shoe magnets sold by cutlers, and those used by potters, as well as magnets for compasses, still use plain carbon steel (0·64 per cent of carbon) for cheap commercial magnets, on account of the price ; but for higher grade magnets they use tungsten steels or other steels of special composition. In France, Allevard steel and Marchal steel are almost exclusively employed. In Germany, Remy steel is undoubtedly the most generally employed. Large quantities of tungsten steel for magnets are every year exported from Sheffield and from Germany into the United States. Tungsten steel is invariably used in the magneto-generators employed for ignition in automobiles. Professor W. Brown examined chromium steels containing from 0·75 to 9·5 per cent of chromium. They have high coercive forces ; but there seems no advantage in adding more than 2½ or 3 per cent of chromium.

A few remarks may be added concerning modern self-hardening high-speed tool steels ; for though their magnetic properties are as yet mostly unexplored, these brands can now be obtained commercially ; and if they can be brought by quenching into the magnetizable state, their extreme hardness would suggest their being possessed of very great coercive force. The Taylor-White high-speed steel, used for tools for turning hard steel, has the composition of tungsten 8·5 per cent, carbon 1·25, and chromium 4 per cent. Another high-speed steel which works well as a tool, even when red-hot, contains tungsten 5, molybdenum 4, and chromium 4 per cent. Other self-hardening steels, according to Brearley, contain very varied proportions ; tungsten from 2·44 to 24 per cent, carbon 0·4 to 2·19, chromium 0 to 6, silicon 0·21 to 3 ; manganese being sometimes used instead of chromium. There is a tendency to use more tungsten and less carbon than formerly ; a much-used proportion being 12 tungsten with 0·8 of carbon. Vanadium steel with 10 per cent of vanadium and 1·1 of carbon, quenched at white heat, is still harder.

We have seen that some kinds of steel will give a remanence of as much as 800 or 900, with various values of the coercive force up to 50, 60, 70, or even 73 (see table on p. 85). We have also seen that some other kinds of steel will give coercive forces of 70 or 75, even up to 80 ; but these generally have values of the remanence (even in cases of zero demagnetization coefficient) under 700. The ideal sought for at the present time is a steel of such composition that, when properly treated, it shall have a remanence of 800 and a coercive force of 80. *No such steel has yet been produced ;* but assuredly it is not unattainable. And with the great modern advance in metallurgical knowledge, it is not beyond the bounds of hope that some day a steel may be produced with a remanence of 1000 and a coercive force of 100. Researches on the alloy steels from this point of view are much needed.

MAGNETIZATION.

All the old processes of single touch and double touch may be at once set aside in favour of the modern method of using an electric current. In the case of bar magnets they are magnetized by putting them inside a long magnetizing spiral at least twice as long as themselves, or for short bars by placing them between the poles of a suitable electromagnet. In the case of horse-shoes they are magnetized by placing their poles in contact with the poles of a suitable electromagnet. In either case the field to which they should be subjected should not be less than $\mathbf{H} = 250$. And, since values twice as great can readily be reached with a magnetizing spiral (requiring, in fact, a circulation of about 1000 ampere-turns per inch length of the tubular coil), this is a simple matter. For horse-shoes, if the electromagnet is one in which there can be a total number of ampere-turns not less than 500 times the number of inches of length along the steel of the magnet, it will suffice, though a higher number has some advantage. For ordinary steels it makes little difference either to the remanence or to the coercive force whether the value of the field to which it is subjected be $\mathbf{H} = 100$ or $\mathbf{H} = 1000$. For hard tungsten steels it is advisable to use the strongest fields available. To produce a field of $\mathbf{H} = 1$ along 1-in. length of air requires a circulation of 2·02 ampere-turns. To produce a field of $\mathbf{H} = 1000$ requires, therefore, 2020 ampere-turns per inch. If a horse-shoe having a total length of 10 in. of steel is to be subjected to a magnetizing force equivalent to $\mathbf{H} = 500$, the electromagnet against which its poles are placed should be excited by at least 10000 ampere-turns; or if its coil is of a wire that will carry 10 amperes, it should have at least 1000 turns—a requirement easily fulfilled. Little depends on the duration of the operation. Lord Rayleigh has shown that the resulting magnetism depends on the maximum value, not on the duration of the applied field. When a very strong magnetizing current is applied only for a moment, the operation is called "flashing." There is a slight advantage in repeating the magnetization a few times by turning off the current, and turning it on again. There is a slight advantage in subjecting the magnet to mechanical agitation, by percussion, during the application of the magnetizing force. There is also a slight advantage in not turning off the current too suddenly, since any electric oscillations produced at the break of the circuit are deleterious. It has at various times been suggested to magnetize the magnet while hot, and to keep it under the influence of the magnetizing forces while it cools. Any advantage gained by this awkward process may be better reached by the simpler way of using when cold a somewhat more powerful electromagnet.

One special arrangement employed at the Thomson-Houston works for magnetizing the magnets used in electricity meters is worthy of mention. These magnets are of a horse-shoe shape with the flat limbs brought near to one another in parallel planes with a narrow gap between them (see Fig. 8). When such magnets are applied to the poles of the magnetizing electromagnet (the poles of which are necessarily very close together), there is a considerable tendency to magnetic leakage across the gap. In order to oppose such leakage and drive the magnetic flux round the bend of the steel, a rapidly revolving copper disc is lowered into the gap during the application of the magnetizing forces; the eddy-currents induced in the disc tending to oppose any flux through it.

MATURING OF PERMANENT MAGNETS.

It is a commonplace that ordinary so-called permanent magnets are apt in the course of time to lose a part of their magnetism and to become weaker. I have already alluded to the deleterious effect of slamming on the "keeper." But there are several causes which contribute to the decay of the magnetism of magnets. Mechanical shock, changes of temperature, contact with other magnets or with iron, exposure to demagnetizing forces, are amongst these. Apparently the mere lapse of time effects a deterioration. Put a newly made and newly magnetized magnet, after measuring its strength on a magnetometer, on a shelf in a dry, cool cellar by itself, and you will find if you measure it again after a few weeks or months that its magnetism will have diminished.* Put it in a window where the sun can shine on it by day, and the periodic warming and cooling of day and night will cause its magnetism to decay more rapidly. Long bars and horse-shoes and other nearly closed forms are found to deteriorate more slowly than short bars; doubtless because their self-demagnetizing coefficients are less. But in all magnets there seems to be a definite law of decay, by virtue of which there appears to be a limit down to which each tends. Briefly, in every newly made magnet, the so-called permanent magnetism appears to consist of two parts, a removable or sub-permanent part which slowly decays, and a really permanent part. Mechanical shocks and charges of temperature promote the disappearance of the removable part; for an old and well-used magnet, though weaker than it was when new, is, as Lamont found,† much more constant in its magnetic power than a new one. The law of decay is illustrated by Fig. 27, where the heights of the ordinates represent the strengths of the magnet, diminishing as time goes on. The height T represents the temporary or removable part of the remanent magnetism, and the height P the really permanent part. The time taken to settle down to constancy, and the proportion that is really permanent, vary vastly with the quality of the steel, and with the dimension-ratio; for in short bars there is always a self-demagnetizing force, proportional to the magnetism present, tending to produce decay, and the soft steels with small coercive force must go on losing their strength until the self-demagnetizing force is so weak that the coercive force is able to

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* Newly hardened steel appears to undergo a slow change for months or years. Brant, in 1909, measured the hardness of 20 rods of Stubbs's steel, which had been made glass-hard by Barus in 1885, and found (using Barus's electrical method of measuring hardness) that they had in twenty-four years lost nearly 20 per cent of their hardness. Other materials show secular changes in their properties. Every thermometer-maker knows how glass after having been melted goes on slightly contracting for many months.

† Lamont found that a new bar magnet lost from 15 to 35 per cent of its strength on being dropped on a hard floor, while an old one lost less than 1 per cent.

cope with it. Assuming that no specially deteriorating actions, such as violent shocks or considerable changes of temperature, etc., are present, the progress of the decrement in strength ought to be logarithmic; hence the curve of Fig. 27 ought to be represented by the equation—

$$y_t = \mathrm{P} + \mathrm{T}\epsilon^{-at}$$

where y_t represents the ordinate at any time t, and where a is the coefficient of logarithmic decrement. This formula was proposed by Hansteen.

Those who are concerned with measurements of terrestrial magnetism have long been aware of the decay of strength of the thin bar magnets used as standards. Measurements of the progressive loss of power of bar magnets have been made by many observers—Lamont, Airy, S. H. Christie, Cancani, Loomis, and others; and the temperature coefficients connecting the variations of strength with rise and fall of daily temperature have often been determined.

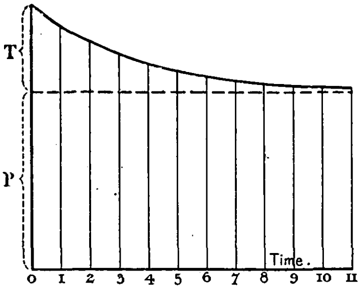

FIG. 27.—Curve of Decay of Magnetism.

Lamont, using thin carbon-steel rods (knitting-needle steel) for terrestrial magnetic measurements, found the decay to be greater in summer then in winter. The following are his data for the monthly losses, taking the initial magnetism as unity :—

	1848.	1849.
January	0·0000	0·0000
February	0·0003	0·0001
March	0·0003	0·0002
April	0·0008	0·0005
May	0·0014	0·0007
June	0·0022	0·0011
July	0·0028	0·0016
August	0·0032	0·0022
September	0·0028	0·0022
October	0·0017	0·0013
November	0·0009	0·0007
December	0·0005	0·0001
Total loss in year ...	0·0169	0·0107

Barrett, Brown, and Hadfield examined a number of alloy steels in the glass-hard stage, as to the amount of loss in six months from their being magnetized in a field of only $H = 45$. They were bars with dimension-ratio of 33. A bar of Swedish charcoal iron of about the same dimensions was added for comparison, with the following results:—

Material.	Chemical Composition.					H_c.	Percentage Loss in Six Months.
	C.	Mn.	Si.	W.	Cr.		
Swedish charcoal iron	0·028	—	0·07	—	—	1·10	40·0
Silicon steel, mild ...	0·220	0·18	0·44	—	—	0·80	11·0
Medium-tungsten steel	0·280	0·28	—	3·50	—	5·70	6·6
High-tungsten steel ...	0·760	0·28	—	15·50	—	12·90	2·7
Tungsten chrome steel	0·250	—	—	2·00	0·75	5·30	14·0
Chrome steel	0·430	—	—	—	3·25	—	3·6
High-chrome steel ...	1·090	—	—	—	9·50	—	10·4

Bosanquet in 1885 made a number of bar magnets of "best cast steel" and hardened them to the utmost. He measured their magnetic moments for several months and found the following average values:—

February 18th	12,039
March 3rd	11,822
March 15th	11,767
April 8th	11,620
September 18th	11,119

Rise of temperature was found by Canton and other observers to produce a temporary fall in the remanence, and fall of temperature to produce a rise; but the percentage change per degree of rise and fall varied greatly, as measured by different observers. If we write the equation in the usual form—

$$M_1 = M_0\{1 + a(t_1 - t_0)\}$$

where M_0 is the magnetic moment at the initial temperature t_0, and M_1 that at t_1° C., and a is the coefficient of change per degree; then a was found by different authorities, for such variations as occur in daily or yearly temperature ranges, to have values varying from $-0·000044$ to as much as $-0·00112$. Wiedemann found that if a bar was strongly magnetized, and then partially demagnetized (by an opposite magnetizing force), it would, on being heated, lose some magnetism if the previous reduction had been small, but would gain some magnetism if the previous reduction had been large. Also, that if a newly made magnet is repeatedly heated and cooled, the magnetization lost at each heating is only partially regained on cooling, causing a progressive loss, until finally a constant state is reached in which the magnetization lost on being heated is restored on cooling. Old magnets are found to be much more constant in this respect. These facts have led to the idea of *maturing* newly made magnets by subjecting them to processes imitating those that go on naturally, with the intent of bringing the magnets rapidly into a state of constancy. Such processes are: (1) repeated gentle heating and cooling, (2) protracted gentle heating, (3) repeated subjection to mechanical shock, and (4) partial demagnetization.

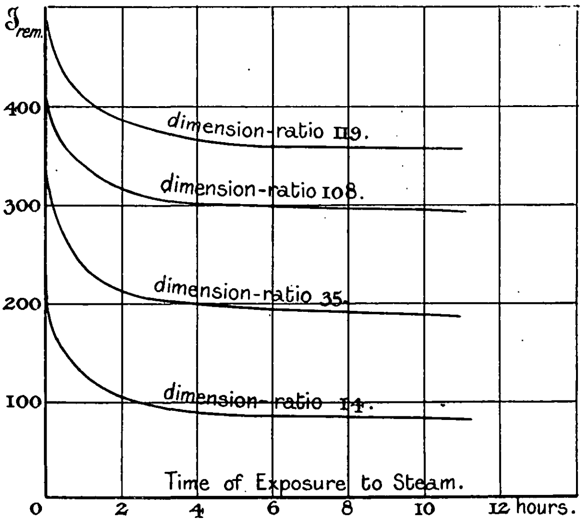

FIG. 28.—Effect of Prolonged Heating to 100° C. (Barus and Strouhal).

We owe to Barus and Strouhal a valuable examination of the beneficial effects of protracted gentle heating. Fig. 28 depicts the results they found on subjecting their glass-hard bar magnets of Stubbs's steel (a carbon steel) to heating by steam at 100° C. for a period of 12 hours. It will be seen that the values of the remanence fell in a regular way, assuming a constant value after some 10 hours of steaming. The final as well as the initial values of the remanence varied with the dimension-ratio. The remanence of that one which was 119 diameters long fell from 488 to a constant value of about 360. Unfortunately, no measurements were made of any change in the coercive force. But measurements of the hardness (by specific electric resistance) showed that this also was reduced *pari passu* to a constant value about 83 per cent of the initial hardness. Barus and Strouhal also observed that the final remanence is the same whether the steaming takes place before magnetization, or whether the rod is first magnetized, then steamed, then remagnetized. In any case, long thin magnets lose a less percentage of their magnetism by being thus steamed than do short ones. In a special research on hardness, Barus found that glass-hard rods of Stubbs's steel, 30 diameters long, lost about 10 per cent of hardness in three years by natural decay, an amount which could have been produced in about three hours by immersion in steam at 100° C. He concluded that mean atmospheric temperature acting on quenched steel for a period of *years* produces a diminution of hardness about equal to that of hot steam acting for a period of *hours*.

To test the effect of this maturing by steam-heating, Barus and Strouhal exposed a glass-hard magnet to 60 hours' steaming, remagnetized it, and steamed it again for 15 hours. Its remanence, originally 320, was reduced thus to a constant value of 258. It was then dropped from heights varying from 1·5 to 0·5 metre on a wooden block, in various ways, and measurements were made of its strength after each treatment. The magnetism did not vary more than 0·54 per cent after any such rough usage.

Mme. Curie examined the effect of reheating on various steels (see p. 110). She found that protracted exposure to steam heat diminished both the coercive force and the remanence. Thus, 10 hours at 100° reduced the coercive force of a 0·84 per cent carbon steel from 51 to 48, and that of Boreas steel from 85 to 78. Reheating to 200° was disastrous, as the following table shows, for three kinds of hard steel.

Square Steel Bars of 20 cm. Length and 1 cm. Side ($\delta = 23$).	Carbon Steel, 0·84 per cent.		Allevard Steel.		Molybdenum Steel.	
	H_c.	I_{rem}.	H_c.	I_{rem}.	H_c.	I_{rem}.
Hardened state	51	422	69	574	79	429
Heated 3 hours at 100° ...	45	415	65	583	73	433
Heated 10 hours at 100° ...	45	396	63	549	71	418
Heated 16 hours at 100° ...	44	397	62	544	70	416
Heated 24 hours at 100° ...	44	390	61	540	70	413
Heated 8½ hours more at 150°	37	363	46	465	50	417
Heated 7½ hours more at 200°	28	310	37	401	40	382
Total loss per cent at 100°	13	8	12	6	12	4
Total loss per cent at 200°	41	27	47	33	50	11

Three other bars were treated at 60° C., with the following results:—

	Allevard Steel.		Boreas Steel.		Molybdenum Steel.	
	H_c.	I_{rem}.	H_c.	I_{rem}.	H_c.	I_{rem}.
Hardened state	70·7	561	79·8	336	82·5	496
Heated 7 hours at 60° ...	69·7	572	78·3	340	79·7	494
Heated 42 hours at 60° ...	69·9	564	79·0	339	79·8	490

In 1887, W. Brown examined the effects of percussion on a number of silver-steel rods, all 10 centimetres long, which after having been made and magnetized were laid aside for different periods, and then examined as to the percentage loss in magnetism that they showed when suddenly dropped from a height. The following table gives the results:—

No.	State.	Diameter.	Dimension-ratio.	I_{rem}.	Percentage Loss due to Percussion, after laying aside for					Total Percentage Loss.
					1 hour.	20 hours.	44 hours.	1 month.	3 months.	
1	Glass-hard ...	0·3	33	324	1·98	2·0	1·95	1·04	0·8	7·77
2	Glass-hard ...	0·2	50	355	2·96	3·2	1·48	1·00	0·0	8·64
3	Tempered yellow	0·3	33	348	6·03	6·1	4·80	5·40	6·2	28·53
4	Tempered yellow	0·2	50	364	4·00	3·5	3·76	2·60	4·0	17·86
5	Tempered blue	0·3	33	422	11·80	10·8	9·71	11·80	7·5	50·60
6	Tempered blue	0·2	50	563	8·20	8·2	8·18	7·50	8·7	40·78

The superior resisting power of the glass-hard magnets is very marked. The superiority of the bars of higher dimension-ratio to those of lower ratio is also evident; the exception in the case of bar No. 2 is probably accidental. Brown finds cylindrical bars with rounded ends less sensitive to percussion than either flat-ended cylinders or ellipsoids of same length and girth. Brown also finds for glass-hard rods of Stubbs's steel that if of 1·6 millimetres diameter there is no advantage as to remanence in making them more than 80 diameters long; and if 10 millimetres diameter, no advantage in making them more than 8·1 diameters long. This result is difficult to understand.

The conclusion is that, in maturing by reheating, both the remanence and the coercive force are diminished for all kinds of steel, but that by prolonged reheating to 60° a constant state is reached, with a reduction, in the case of the best steels, of from 1 to 3 per cent only.

Mme. Curie also investigated the effect of maturing on the liability to loss by shocks. A number of similar bars were dropped, end-on, from a height of 85 cm., upon a flag-stone, and then dropped, broadside-on, from a height of 30 cm., upon the same stone. After each repetition of this process the magnetism was measured, and the process was repeated till a constant value was obtained. Bars of soft steel lost from 45 to 83 per cent of their remanence. For the others the following table gives the chief results :—

Bars of Dimension-ratio $\delta = 23$.	Bars in Hardened State.				Bars matured at 100° C.		
	H_c.	I_{rem}.	No. of Falls.	Loss per Cent.	H_c	No. of Falls.	Loss per Cent.
Carbon steel (0·5)	23	210	30	0·23	22	20	20
Allevard steel ...	73	560	50	0·50	68	100	7
Boreas steel ...	86	390	5	1·50	—	—	—
Molybdenum steel	73	448	10	2·90	69	30	3

The effect was then tried of subjecting some of the same bars (dimension-ratio 23) to a partial demagnetization to mature them, and they were then tested by shocks of the same sort as before. The values of I_{rem} are given here for two bars :—

(1) *Carbon Steel* (0·5 per cent carbon).	I_{rem}.
Bar magnetized to saturation	200·0
After many shocks	152·0
Remagnetized, then demagnetized in field $H = 8·5$	150·0
After many shocks	Lower
Remagnetized, then demagnetized in field $H = 13·8$	118·4
After 4 days had spontaneously increased to ...	123·0
After many shocks, remained constant	123·0
(2) *Allevard Steel.*	
Bar magnetized to saturation	676.0
After many shocks	658·0
Remagnetized, then demagnetized in field $H = 6·4$	663·0
After many shocks	636·0
Remagnetized, then demagnetized in field $H = 14$	632·0
After many shocks, constant at	632·0

It appears that a reduction of about 6 per cent rendered the Allevard bar insensible to shocks, while the carbon-steel bar had to be reduced by about 40 per cent to attain constancy. Mme. Curie found that for all such bars, if of really hard steel, a reduction of 10 per cent sufficed to render them immune from shock. For longer bars or for more nearly closed circuits the reduction necessary would of course be less. Moreover, magnets so reduced by about 10 per cent are immune from loss by changes (over a limited range) of temperature. A bar of Allevard steel, hardened and matured at 60°, and then fully magnetized, will lose a little if again heated to 60° and cooled. But if its magnetization be reduced by about 10 per cent it will be immune from loss by a subsequent heating to 60° and cooling. For bars so treated the temperature coefficient is about —0·0002 for Allevard steel and —0·0003 for molybdenum steel.

Mme. Curie also found that the intensities of the fields required in these bars to reduce their magnetization by 10 per cent was:—

	H_c.	Field needed.
Carbon steel (0·5 per cent carbon)	21	3·5
Allevard steel, hardened, and matured at 60°	71	13·0
Boreas steel, hardened, and matured at 60° ...	78	27·5
Molybdenum steel, hardened, and matured at 60°	80	21·0

In a series of memoirs Klemenčič has carried inquiry a little further. He used tungsten-steel bars of Böhler & Co. of five different brands marked "O," "OO," "UI," "43," and "45." They were magnetized in a field of H = 865, produced by a magnetizing current that was several times reversed and suddenly switched off. He investigated the relation between the dimension-ratio and the temperature coefficient; the figures being deduced from three series of his observations (see table on page 129).

He concluded that the temperature-coefficient varied inversely as the dimension-ratio. If the magnetizing current was gradually reduced instead of being abruptly broken, the remanent magnetism was found to be slightly higher, the augmentation being from 0·1 per cent for long thin rods, to as much as 5 per cent for short thick ones. The difference was ascribed to the action of eddy-currents in the steel.

Another point tested was the decay of the remanence with time. The percentage loss was found to depend on the dimension-ratio.

An average of the various brands of steel showed that glass-hard magnets with dimension-ratio 10 lost from 3 to 4·5 per cent in 15 months, while those with dimension-ratio 25 lost only from 1·25 to 1·98 per cent in the same time. Another set of bars of dimension-ratio 25 were matured in steam for 12 hours. After a year they had lost from 0·12 to 0·25 per cent of their magnetism, of which the greater part occurred within a day or two of their being made. In the following 11 months the percentage losses were from 0·025 to 0·0134 only.

Another point investigated was the influence of allowing time to elapse between hardening and magnetizing. A number of silver-steel rods were hardened, and then, after lapse of time varying from 0·6 of a minute to an hour, were magnetized. Their magnetic moments were then measured at regular intervals of time, and the decay was observed. It was found that the regular fall in their strengths was practically independent of the time when they were magnetized, and depended only on the time that had elapsed since they were hardened. This proves that there is a sort of self-annealing going on in the newly hardened steel, and that this molecular settling down of the material is scarcely influenced by the process of magnetizing. Further, though the percentage decrease in magnetization is practically the same for all rods, if reckoned at the same length of time from the hardening, yet the absolute value of the remanence (at the same lapse of time since hardening) is less the earlier the rod was magnetized after hardening. It is good to let the steel settle down before magnetizing. The settling down is hastened by boiling at 100°. The conclusion is that the secular changes—at any rate in magnets of the older carbon-steel kinds—are sequelæ of the hardening process and are not sequelæ of the magnetizing process.

Dimension-ratio.	Species of Steel.		
	"45."	"UI."	"OO."
10	0·000445	0·000480	0·000281
15	0·000300	0·000345	0·000186
20	0·000215	0·000265	0·000139
25	0·000172	0·000215	0·000145
38	0·000134	0·000139	0·000139

Krüse, continuing the researches of Klemenčič on Böhler's steels, examined their behaviour when subjected to shock, and to the effects of bringing them into contact with masses of iron from which they were suddenly pulled away. The magnets were matured on the plan of Barus and Strouhal, and were then caused to fall on a marble slab 20 times from a height of 1 m., and then 20 times from a height of 1·94 m. The following were the results :—

Brand of Steel.	"45."	"43."	"UI."	"OO."	"O."
Coercive force	57·0	59·0	63·0	76·0	84·0
Percentage loss when $\delta = 10$	6·7	8·2	5·9	4·8	4·4
Percentage loss when $\delta = 25$	6·7	5·9	5·5	5·4	3·5

It will be seen that the percentage loss was least for the brands which had the greatest coercive force.

Krüse also investigated the effect of placing cylinders or plates of soft iron in contact with the ends of his matured bar magnets and then suddenly pulling them off. This is a matter which the author investigated* for horse-shoe magnets over twenty years ago, and found that while a magnet was weakened by slamming the keeper on and gently sliding it off, it was strengthened by sliding it on and suddenly detaching it. Krüse found by a repeated detachment a decrease of about 0·1 per cent for magnets of dimension-ratio 25 and of 0·3 per cent for those of dimension-ratio 10. He does not say whether the iron was slammed on or not. Newly magnetized and matured magnets showed an increase of about 0·5 per cent. Drawing the magnets over the face of an iron plate weakened the magnets by about 20 per cent for those of $\delta = 25$, and by about 28 per cent for those of $\delta = 10$.

Thomas Gray, in 1885, examined the percentage changes of magnetization produced in bar magnets of silver-steel that were produced by placing them in a weak demagnetizing field of value $\mathbf{H} = -1$. The reduction so effected varied from 0·8 per cent for bars of a dimension-ratio of 10, to 0·43 per cent for those of a dimension-ratio of 100.

It is much to be desired that some investigator would make an examination of tungsten steel and other alloy steels, as thorough as that of Barus and Strouhal on carbon steel, as to the effects of maturing, by heating and partial demagnetization, in rendering them immune from change by shock or temperature.

Ascoli compared Allevard steel with Glisenti steel (see page 116) in respect of their ability to withstand shock. He also determined the percentages to which the respective magnetizations must be reduced to secure final stability of the permanent residuum. The

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* Silvanus P. Thompson, *The Electromagnet* (1892), pp. 213 and 408.

results are embodied in the following table. The magnetizing fields were $H = 100$ or a little more.

Dimension-ratio.	Percentage Loss by Shock.		Percentage Reduction for Stability.	
	Allevard.	Glisenti.	Allevard.	Glisenti.
10	29·2	30·3	18·6	22·4
15	16·5	17·0	21·6	22·2
20	10·9	11·1	19·4	22·6
30	5·7	5·9	18·6	20·5
40	4·1	4·0	—	—
50	3·5	3·2	12·4	16·6
100	2·6	2·3	9·4	10·3
∞	2·4	2·1	8·2	8·7

It will be seen that while Glisenti steel lost less by shock than Allevard for long magnets, it lost more for short ones, and required a greater reduction to become stable.

Ashworth has studied the temperature coefficient, and the coefficient of permanent loss which a magnet undergoes by being heated (once) from room temperature to 100° C. and again cooled to room temperature. His results relate chiefly to pianoforte wires of drawn steel of an unknown composition. He found drawn steel to be in a peculiar molecular condition, such that for $\delta = 109$ its temperature coefficient is positive until it has been once heated red-hot, after which the coefficient is like that of other steels, negative. For a dimension-ratio of 43 such a drawn wire had zero coefficient. He found hard steels to have the lowest temperature coefficients. In the following table I_i represents the initial remanence, and I_f the final remanence after being raised from 14° C. to 100° C. and again cooled to 14° C. The symbols α and β are respectively the ordinary temperature coefficient (according

Material.	δ.	I_i.	I_f.	α.	β.
"Magnet steel" (carbon), hardened ...	8·0	53·2	40·6	—0·001370	—0·270
Mushet steel, hardened	12·0	185·9	132·6	—0·000690	—0·287
" " "	17·0	215·2	177·8	—0·000970	—0·174
Cast iron, hardened ...	11·8	193·1	167·8	—0·000180	—0·131
" " ...	13·1	210·9	180·1	—0·000160	—0·141
Piano wire, glass-hardened...	16·0	252·0	216·0	—0·000603	—0·150
" "	48·0	551·0	520·0	—0·000228	—0·090
" "	80·0	570·0	580·0	—0·000097	—0·030
" "	96·0	556·0	569·0	—0·000055	—0·020

to Whipple $-0{\cdot}00029$ in the average), and β the coefficient of the irreversible or permanent loss.

Doubtless the values of β would have been greatly reduced had the magnets been properly matured. The dependence of these coefficients on the dimension-ratio is well illustrated by the data on glass-hardened piano wire.

Cancani found bars of "English steel," which were about 11 diameters long, to possess a temperature coefficient, when glass-hard, of as low a value as $-0{\cdot}000436$, but when annealed soft, of as high a value as $-0{\cdot}002635$. When such glass-hard bars were tempered by regular stages from pale straw (at 221°) to a pale green (at 332°) the temperature coefficient rose in regular sequence from $-0{\cdot}00135$ to $-0{\cdot}00179$.

Durward has examined matured bar magnets of various kinds of steel, and has shown that in "crescent" drill rod (a tungsten steel), matured by Barus's process, the coefficient of loss β varied from about $-0{\cdot}0012$ for a diameter-ratio of 5, to $-0{\cdot}0006$ for $\delta = 10$, $-0{\cdot}0003$ for $\delta = 20$, and $-0{\cdot}00025$ for $\delta = 32$.

CAST-IRON MAGNETS.

At various times cast-iron has been proposed as a material for permanent magnets, and B. O. Peirce, in 1905, showed that chilled cast iron, though inferior to tungsten steel, yet would make good magnets. Ashworth (see p. 131) had shown that its temperature coefficient is low. Campbell, in 1906, showed that if quenched at about 1000° C. —a difficult operation because of the brittleness of the material—its coercive force is quite equal to that of the carbon steels; and he found values of the remanence from 200 to 229, and coercive forces from 48·9 to 52·8.

PRACTICAL PROCESSES FOR PRODUCING THE BEST PERMANENT MAGNETS.

We may sum up the results in a few paragraphs. To produce permanent magnets, which are both powerful and constant in their power, a tungsten steel should be used having from 5 to 8 per cent of tungsten, and from 0·4 to 0·6 of carbon. Chromium up to 2 or 2·5 per cent may be present, but the presence of the following elements should be avoided: manganese, titanium, copper, sulphur, and phosphorus.

For bar magnets there is an advantage in having the dimension-ratio as large as possible, as this gives not only a higher remanence but a lower coefficient of temperature variation. For horse-shoe magnets, and for all those which are to be used in instruments where extreme constancy is required, the gap between the poles should be as short as possible, and the polar areas should be as large as possible. From the point of view of constancy there is an advantage in having a considerable stray flux (through a magnetic shunt or otherwise) in addition to the useful flux.

The forging of the magnet, whether bar or horse-shoe, should be done with as little working of the material as possible, and at as low a temperature as is convenient. After forging, to normalize the material it should be heated to 900° C., lowered to 750° C., and there maintained for a time, then cooled off. To harden the magnets, they should be raised to 950° C. for a period not exceeding 5 minutes; and then lowered to about 700° C. and quenched at this temperature in brine or oil, at a temperature under 20° C. Some brands of high tungsten steel appear to yield a better result if quenched at some temperature between 770° and 850° C., or even at higher temperatures.

With tungsten steels there appears to be no advantage whatever in tempering the steel. With carbon steels there is no advantage in tempering the magnet if it is one having a small dimension-ratio (as for short bars). But bar magnets of carbon steel, if their length is as much as 20 diameters, may be tempered to a straw tint; or if as much as 40 diameters long, or more, they may be let down to a blue tint, and will then receive more magnetism. Any letting down below a straw tint, however, impairs their power to resist decay and usage.

The magnets should then be matured either by boiling or steaming them for ten or twelve hours, or by heating them to 60° C. for 20 or more hours. There is some advantage in letting them cool several times during this process. For a magnet that is intended to be used at some particular temperature, and is required to be as constant as possible at that temperature, there is some advantage in subjecting it to a number of cyclic processes of alternately heating it to a few degrees above, and cooling it to a few degrees below, that temperature at which it is intended thereafter to be used.

The magnet should then be magnetized by means of an electro-magnet, or, if a bar magnet, in a powerful magnetizing coil, to the highest degree of magnetization possible. There is some advantage in reversing its magnetism a few times. There is no advantage in magnetizing for a long time, as the result depends on the maximum magnetizing force applied, and not on the duration of the application. But in the final magnetization the magnetizing current should not be suddenly switched off, but should be diminished gradually to zero. There appears to be a slight advantage in subjecting the magnet during magnetization to mechanical percussion, by striking it with a hammer of brass or other non-magnetic hard material.

For magnets that are to be given extreme constancy, there is an advantage in then slightly reducing their magnetism by subjecting them to demagnetizing forces, a reduction of from 5 to 10 per cent being sufficient. It is doubtful whether this process is necessary* for magnets the form of which is a closed circuit with a very narrow gap.

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* Mr. George Hookham kindly informs me that for meter magnets the firm of Chamberlain and Hookham do not resort to partial demagnetization. "We flash our magnets," he says, "to saturation, and never think of reducing them, and find them sensibly permanent—that is, if they have only the air-space to deal with. If they have other reversing influences to contend with, as in alternating-current meters, then we may reduce them."

There is supposed also to be some advantage from the point of view of constancy in subjecting the finished magnet to percussion.

The rationale of the advantage of reducing the power of the magnet by a partial demagnetization is worthy of a brief consideration. On p. 92 above were set forth the reasons why the self-demagnetizing factor of a magnet reduces the remanent magnetism; and in Fig. 10 was given a graphic construction, due to Ascoli, explanatory of the same. Ascoli has himself further studied the stability of the remanent magnetism, as have also Du Bois and Taylor Jones. It was remarked long ago by Ewing that if at any point of a hysteresis loop the magnetizing force is partially reduced and then raised again, the resulting curve shows a subsidary narrow loop, the slope of which is, in general, quite small. That is to say, at every stage of magnetization there is a removable part of the magnetism which vanishes on a partial demagnetization and is again restored on the cessation of the demagnetizing force. And for this reversible part, the quasi-permeability

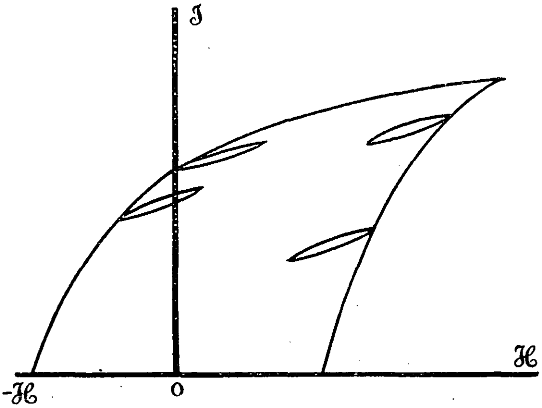

FIG. 29.—Subsidiary Hysteresis Loops.

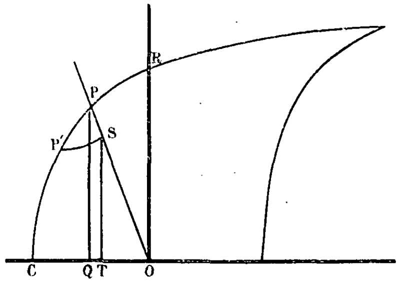

FIG. 30.—Diagram of Partial Demagnetization.

is small. Fig. 29 shows a number of loops corresponding to such small cycles of operation. Now consider a permanent magnet of such steel that the remanence, if all demagnetizing influence were absent, would be represented in Fig. 30 by the height of the line O R. Now let there be a self-demagnetizing coefficient, and let the line O P be drawn at such a slope that the tangent of the angle R O P represents the demagnetizing coefficient. Drop the perpendicular P Q. O Q will represent the actual self-demagnetizing magnetic force. Then the remanence will be reduced to P Q; and though O C is the coercive force of the material, yet it is only the excess of O C over O Q, namely, the length C Q, which represents the reserve that the magnet has to resist external demagnetizing influences.

Now let the magnet be slightly further temporarily demagnetized by an external demagnetizing force down to the point P′. On removing this demagnetizing force the magnetism will spring up to S; the height S T now representing the permanent magnetism that is left behind, and which is, say, 10 per cent less than P Q. Although the remanence is thus reduced, yet the stability will be greater. For the self-demagnetizing force is now only O T, and the length C T, which represents the reserve of coercivity of the magnet, is greater than before.

But we may carry the process a stage farther. After applying a small external demagnetizing force to bring the value down to P′, apply an equal small remagnetizing force, and bring the magnetization up, as in Fig. 31, to the point U. Then remove this external force, when the narrow loop will return from U to a point on the line O P at S′, at the height S′ T′. The result is then that the permanent magnetism will be represented by the line S′ T′, which is slightly greater than S T, while the reserve of coercivity C T′ is almost as great as before.

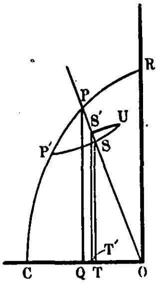

FIG. 31. — Diagram of Stabilization by Subjecting to Small Cycle of Magnetizing Forces.

It would, indeed, be advantageous to repeat this small cycle several times over, so as to bring the magnetic state into a final condition, where the effects of any accidental external magnetic influences will be a minimum. In brief, just as the thermal stability of a magnet is best assured by subjecting it to small cycles of heating and cooling about the point of temperature at which it is thereafter to be used, so its magnetic stability is best assured by subjecting it to small cycles of demagnetizing and remagnetizing force about the point of magnetization at which its magnetism is thereafter to remain constant.

CONCLUSION.

After the remarks made in the course of this lecture as to the need of research in various directions, both as to the production of alloy steels of the desired magnetic properties and as to the further studies of their magnetic and thermal constants, it is needless to enlarge on the field that is open for extensions of knowledge. There must be co-operation between the steel-makers on the one hand and the physicists on the other hand in any such investigations. Magnet steel of high quality is in great demand to-day. We know that the Sheffield manufacturers are alive to the demands of modern science, particularly in the matter of special steels for tools, in which they were the pioneers. Even to-day, in spite of all tariffs and all competition, they are sending vast quantities to America and to the Continent. But only lately I heard that an order for 300 tons of magnet steel at £60 a ton had been placed with a firm having no connection with Sheffield. The production of magnet steel is a branch of business which, even more than the manufacture of tool steel, depends on the co-operation of science with industry. Certainly our Institution will not be slack in endeavours to bring about such a co-operation, when once the interests involved are realized, and the problems awaiting solution have been set forth in the light of day.

[A number of permanent magnets of different forms, constructed by different firms, Messrs. W. F. Dennis & Co. (Remy steel), MM. Ch. Pinat et Cie, of Allevard, Messrs. the Thomson-Houston Company, and Messrs. H. Shaw & Sons, of Sheffield, were shown upon the lecture-table.]

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