ELECTRO-MAGNETS.[1]

BY J. T. SPRAGUE.

THERE is still some confusion about the meaning of the "strength of a magnet," and the various terms, "magnetic moment," "free magnetism," "magnetic force," and "lifting power." It is not intended to deal with these subjects here, except so far as is necessary to explain the principles of electro-magnets, but it is essential to make clear the distinction between magnetic strength and lifting power.

1. The *strength of a pole* is measurable by the field it can set up or by the attractive or repellent force it can exert upon another magnet. The *unit* strength of pole is that which at one centimetre distance repels a similar and equal pole with a force of one dyne.

2. Now the essential feature of magnetism is its equal opposite dualism; in every magnet there are equal N. and S. forces present; in every magnet there must be a N and S. end, and in some sense a N. and S. pole; but it by no means follows that the two ends of, say, a bar magnet, constitute *two poles of equal strength*, for one pole may be stronger than the other, notwithstanding the equal opposite magnetism.

3. Taking a bar magnet, equally magnetized throughout, and having equal opposite N. and S. poles, either end may be capable of lifting a fixed weight—say, 1 oz.; let the bar be formed into a horse-shoe, and it will no longer lift only the weight due to its two poles, but several times that weight. Lifting power, therefore, depends upon something besides magnetic strength; it depends upon the arrangement of the poles, or really upon how much of the whole magnetic force is concentrated within the armature by which the lifting power is exerted. Figures 1 and 2 will explain these relations. Figure 1 is a bar of iron with a helix over its whole length, giving equal magnetism throughout, and constituting equal N. and S. poles. Now, if we assume that pole N. can hold up 1 oz. weight, when a current passes sufficient to *saturate* the bar, we can make it hold a greater weight with the same current by adding a piece of iron to the S. end. We can do so because we have increased the *magnetic capacity* of the system. Figure 2 represents this result attained in a different way, that is by using a longer core to the same helix. Now we have no longer equal magnetism throughout the core; we have equal N. and S. magnetism truly; but the middle or neutral point of the magnet would no longer be at the middle of the bar, but brought considerably nearer the N. end; therefore, the N. pole would be stronger than the S. pole, and would hold a greater weight, because the lines of magnetic force are of necessity more concentrated at that end.

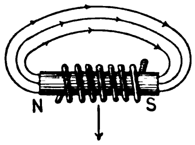

FIG. 1.

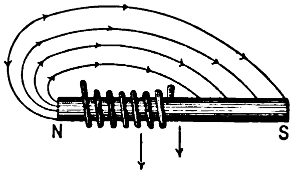

FIG. 2.

4. The action of the horse-shoe magnet is like that of the straight bar, so far as its internal forces are concerned, but its polar ends are brought so near each other as to concentrate its field of force into a small space, and to enable it to induce powerful magnetism in an iron armature entering into the field and absorbing all its lines, so as to form a closed magnetic circle. Therefore, in a horse-shoe, the difference between pole strength and lifting power is not only so much greater than in a bar, as before stated, but this difference becomes greater the nearer the ends are brought together—that is to say, the same electro-magnet will have a smaller field for action at a distance, yet with greater lifting power, if its poles are 1 in. apart, than if they are 2 in. apart. The reason is that the magnetic force becomes more intense when exerted upon the smaller mass of the shorter armature.

5. Therefore, all the common statements as to laws of attraction are mere fables; each particular construction has its own action, dependent upon the nature of the field it produces. But there are proportions of the several parts of the electro-magnet from which the maximum advantages are to be obtained, corresponding to the desired conditions. As to this particular point of attraction, we have at once this rule; *if great holding power, or great attractive power at a short distance is required, bring the poles near each other, either by construction or by pole pieces; if a more even and distant action is desired, open the polar space.*

6. Figures 3 and 4 will serve as references to explain the proportions. C and D are the cores on which helices are placed, the latter being wound upon the reel or spool H. B is the yoke which connects the cores together, and A is the moving armature. The best relation of these is that they should be of equal lengths, that B, the yoke, should be of greater mass of metal than the cores, and A, the armature, of equal mass, but spread out into a broader surface, in order to readily absorb the lines of force issuing from the ends of the cores.

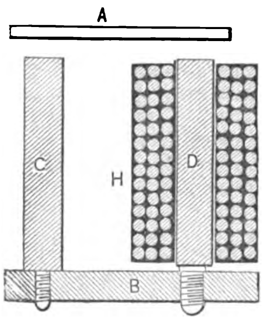

FIG. 3.

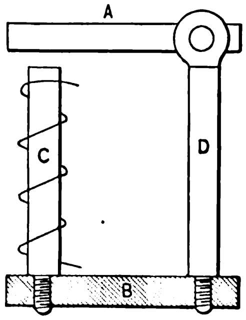

FIG. 4.

7. Figure 4 shows a method of obtaining sharp attraction on an armature by hinging it to the end of one pole, so that it plays angularly through a small space, and is very quickly magnetized from that pole; instead of hinging, the pole may be slightly rounded and fitted with a pin passing through a conical hole in the armature. The core D may in many cases be left without a helix, so that it acts like the polar extension in Figure 2.

8. The *cores* carrying the helices should each have a length of six times their diameter, or twelve times in the case of a straight bar.

The *helix* should be of the same thickness as the core, making its diameter three-fold that of the iron core.

These dimensions of maximum efficiency are found to result from the combinations of a variety of functions.

9. *Cores* vary in magnetic strength in the ratio of the *square root of their diameters* and also of the *square root* of their lengths. *Lengthening the core* distributes the field to a greater distance, and increases residuary magnetism; therefore, magnets intended for rapid working should have short cores.

10. *Hollow* cores are as effective as solid metal of equal diameter, provided the tube or shell is sufficiently thick to absorb the full effect of the current; one-fourth the diameter is usually sufficient, but the ends of the tubes must be closed with iron plugs somewhat thicker than the shell. The best mode of forming such cores, when small, is to drill out the solid metal to the required depth, and then to slit the tube lengthwise, to prevent the formation of induced or Foucault currents in the core at every change of the magnetic condition.

11. The six-fold length and unit thickness of helix is that which (combined with above ratio of core) gives the greatest magnetic result for the shortest length of wire.

---

[1] From the *English Mechanic*.

Within practical limits, each *spire* or convolution of wire, whether close to or distant from the core, has equal magnetic effect; but one turn of the distant wire would make two turns of wire of half the diameter, and therefore have double magnetic action for the same resistance; on the other hand, lengthening the helix to gain this would reduce the total magnetism by increasing polar length, and diminishing the number of turns at each section.

12. Concentrating the wire of the helix, for a fixed length of wire, at the polar ends, as in Figure 2, adds to the polar force in a bar magnet (at one end) so long as one-third of the core is covered. Professors Ayrton and Perry compared four bars, each 1 ft. long and ⅜ in. thick, with equal lengths of wire wound—1, equally over the whole; 2, coned to each end; 3, equally over half the length; 4, on half and coned towards the end. The lifting powers and distant actions upon a needle were with the same current, which was below the limit of saturation.

1 lifted 45oz., widest field
2 " 57oz., weakening
3 " 57oz., at equal
4 " 77oz., distances.

In horse-shoe magnets better effects are obtained by even distribution of the wire upon the two arms; but if a very small and quick play of the armature is desired, the wire may be brought more closely up to the ends.

13. The magnetic strength is proportionate *to the current* and also to the *number of turns* in the helix. It is usual in formulæ to express this as $C\,t$; but it will simplify the conception of the law of action to combine the two into one fact, and say it is as the *current turns*. Even this is indefinite, and it is still better to add another to our unit system, and collate magnetic effects to the *ampère turns*, to which a few experiments would give a definite value.

We may obtain a certain magnetic strength from a given core under many varying conditions of current. Thus 100 turns of thick wire carrying a 10 ampère current = 1,000 ampère turns; 1,000 turns of a smaller wire with 1 ampère current, still = 1,000 ampère turns, and 10,000 turns of fine wire with current, 1 ampère gives also 1,000 ampère turns. Each would constitute a magnet of equal strength, and it would depend upon the resistance of the circuit and the electromotive forces at disposal, which organization would be best suited to any given case. To equally magnetize two cores of different diameters (that is, to bring two masses of the same quality to the same degree of saturation), the ampère turns must be in the proportion of the square roots of the cubes of the diameters.

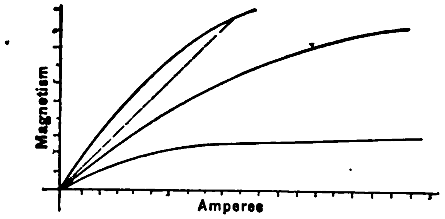

FIG. 5.

14. But this law only holds good within a certain range of magnetic increase. If we were to express it diagramatically, the growth of magnetic strength in any given magnet would be represented by the dotted line in Figure 5, and would rise indefinitely with the current. But the action is a steadily diminishing one, such as is represented by the three curved lines, which all tend to a limit at which increased current does not add to magnetic strength. This is the limit of *saturation*.

15. The limit of saturation is different for different materials. The lowest curve of Figure 5 represents the *capacity* of hard steel, and the others the capacity of different qualities of iron, showing that the *same current* will develop different magnetic strengths in different irons, so that one quality will reach its limit of saturation at a point far below that of another. Soft iron has, in fact, eight times the capacity of steel, which is the reason that electro-magnets are better than permanent ones for dynamo machines.

16. *Steel* has two limits of saturation. 1. That to which it can be carried by an electro-magnet, or even by the old processes of magnetizing. 2. That which it will retain under ordinary circumstances; between these two limits it reacts with currents as iron does, giving up the excess charge of energy in the form of induced currents.

17. It is in the neighborhood of this lower limit of permanent magnetism of steel and regular magnetic increment that the law of ampère turns applies, and it is also at about this range that electro-magnets will do their best work. It is evidently bad economy to force them up towards saturation, for two good reasons. 1. It requires growing increase of current to proportionately increase the magnetic strength. 2. The increase of current involves expenditure of energy in the ratio of the square of that increase, besides the extra loss from resistance due to the heat generated in the wire.

18. The maximum attractive power capable of being developed in iron was found by Joule to be 200 lbs. per square inch of core surface, equivalent to a force of 13,800,000 dynes per centimetre. Prof. Rowland gives the capacity of iron at 1,390 C. G. S. units per cubic centimetre; but various authorities range from 400 to 1,000 for steel, and, as will be understood from Secs. 15 to 18, each quality of iron has its own specific capacity, to be ascertained only by experiment.

19. The selection of the most suitable size of wire is determined by the resistance of the rest of the circuit. For maximum work, irrespective of other considerations, the resistance of the helices of the electro-magnet should be equal to that of all the rest of the circuit, including the battery. For rapid action, as in a vibrating armature or telegraphic relay, the resistance should be made much lower than this, to prevent the counteracting influence and damage of extra currents. But it should be understood that the term resistance is employed in this way merely as a convenient means of measuring and comparing the wires of different sizes and lengths, which can be put into the helix of certain required dimensions. Resistance, as such, is objectionable and must be kept as low as possible by the use of wire of a high conductivity.

20. Various formulæ are given for determining the sizes of wire required; but I prefer, for the sake of general readers, to deal with the subject physically rather than algebraically. A helix is a certain space which is measurable in cubic inches, or, as it is usually round, in cylindrical inches, by taking the square of the external diameter, and deducting from it the square of the diameter of the internal tube, which gives the sectional area of the wire space, and this, multiplied by the length of the helix, gives its capacity; then, multiplying by 2,247 grains per cubic inch, or 1,765 per circular inch, we have the weight as solid copper. From this a deduction has to be made, varying with the size of the wire and the nature of its covering, and also with the skill employed in winding it on the helix. In the case of silk covered wires, it will vary from .75 for wires about 16 to 20, .60 down to 26, .50 at 32, and .30 at 40 gauge.[2] The solid weight, multiplied by these ratios, will give the actual weight of metal which can be placed on the helix.

21. Having thus the weight of metal at disposal, W, and the resistance it is to give, R, we can ascertain the diameter of wire to be used. In fact, a simple rule-of-three sum will give us the ohms per pound—

As W is to 7,000 grains, so is R to ohm lb.

A reference to the table given in most works on practical telegraphy will then show the suitable size of wire, or it may be calculated from the constant of 1 mil. wire

---

[2] These numbers refer to the Birmingham gauge.

$\frac{3,416,825}{\text{ohms per lb.}}$ = square of area in mils. of the required wire.

Therefore, the square foot of the quotient gives the area, and the square root of this the diameter.

The logarithmic calculation is exceedingly simple, as it consists only of deducting the logarithm of the ohms per lb. from 6·5336228, and dividing the remainder by 4, which gives the logarithm of the diameter required.

22. The simplest mode in practice of ascertaining the proper ratio is to prepare a mandrel, in which are cut recesses exactly 1, 2, or 3 inches long, to suit different sizes of wire, and to wind a layer of wire in one of these, so as to learn the exact number of turns per inch. The diameter of the bare wire will give the number of turns of it which would occupy the inch, and the difference is the space occupied by the covering.

23. The first thing to be considered in designing an electro-magnet, is the definite mechanical work it is to be required to perform. Every action means the expenditure of a certain definite amount of energy which can be measured in foot-pounds, and the construction of the magnet must be such that the current passing it will supply this energy, which, for the time being, acts as a resistance added to that due to the wire itself. In designing the electro-magnet it is necessary, therefore, to adapt the size of the core to the dimensions which will give the attractive power which is calculated as necessary, and afterwards to adjust the size of the wire and its resistance to the conditions of the circuit, because, while a stout wire may give the required conditions close to the source of the current, a fine wire may be necessary at any considerable distance.

Then the battery power must be arranged to give, not merely the current required to pass in the magnet, but the electromotive force necessary to pass that current when the magnet is doing work; it is here that failure generally arises.

24. Set up a battery and magnet with a galvanometer in circuit, and note the current; now give the magnet work to do in holding up a weight, and *the same current will no longer pass.* This seems a paradox, that a smaller current should pass when it has to do work than when it merely traverses the wire; but it is easily explained. Let the battery and magnet have each a resistance of 1 ohm, and the battery an E. M. F. of 6 volts, so as to pass a current of 3 ampères, and let us assume, for the convenience of figures merely, that the added work reduces the current to 2 ampères. This means that *the work is equivalent to a resistance of* 1 *ohm* added to that of the wire. Now the energy expended in accordance with Joule's law, is in the ratio of $C^2 \times R$, be the resistance of what order it may. Hence, we have, at first energy supplied by the current $3^2 \times 2 = 18$ joulads[3] per second.

Under the second conditions, we have it $2^2 \times 3 = 12$, less energy supplied by the reduced current to the increased resistance.

But in the first case, the whole 18 joulads are expended in heating the battery and wire; in the second case, only 8 are so expended, while 4 are employed in work.

25. If, then, the magnet is so arranged that it will require 3 ampères to do its work, it is evident the E. M. F. must be increased in proportion to the extra resistance represented by the work; it must, therefore, be raised to $C \times R = 3 \times 3 = 9$ volts, and then we shall have energy $3^2 \times 3 = 27$ joulads, of which 18 are used in battery and wire as before, and 9 remain to do the mechanical work. Therefore, in all cases, the battery must supply the current required while work is doing, not merely that calculated from the measured resistances.

26. As usually constructed—that is, in the horse-shoe form—the electro-magnets do not utilize all the magnetic effect of the current, which acts externally as well as internally, but in the opposite direction. The armature is magnetized, of course, but only by induction from the core, and part of the power must be diverted to the external field of the helix. This external power may be utilized in various ways.

27. A few years ago, great claims were made as to the advantages of surrounding the helix with an external tube of iron connected to the core at the lower end by a disc of iron. This was patented under the name of the "altandi" magnet—a barbarous word invented to convey some idea of exaltation; but the construction had been frequently employed before. Figure 6 will explain it.

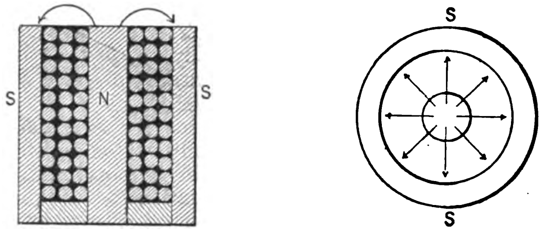

FIG. 6.

It will be seen that though there is only one core, this is still a true horse-shoe magnet, the other arm being a cylinder surrounding the core. The effect is to produce an intense, but very limited field, represented by the arrows, giving, no doubt, great holding power, but with attraction exerted only at a small distance.

28. A modification of this has been employed in some electric bells, which is shown in Figure 7.

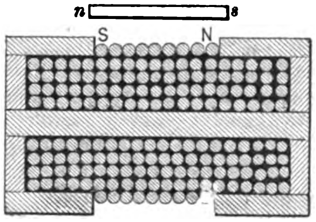

FIG. 7.

In this a cylinder is placed on each end, and the opening in which the field is produced is at the middle of the core.

29. Perhaps the greatest power may be obtained by a further modification of my own, in which the external action of the current is taken up by the armature, which is thus magnetized by the current, as well as by induction. Figure 8 shows this:—

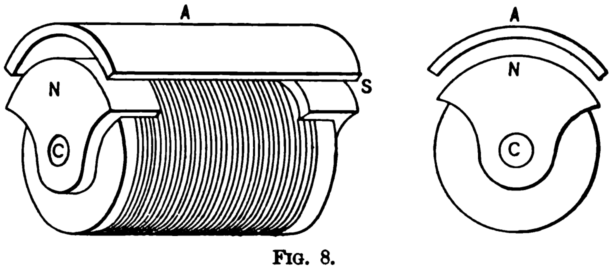

FIG. 8.

C is the core, fitted with two pole pieces, N, S, extending over one-third of the end of the helix; A is the armature in which the outside action of the current produces poles *n s* opposed to those of the magnet, so that a powerful attraction draws down the armature which constitutes part of a cylinder fitted to the pole pieces.

---

[3] The term *joulad*, is here used to express the unit rate of doing work, now more usually termed a *watt*.—[Editor.]