PERMANENT MAGNETS and Their Application

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Preface

The modern permanent magnet is a convenient medium for the transfer of energy from one form to another and is an essential component in a variety of devices. Many new magnet materials that offer the designer new design latitudes have helped make the permanent magnet popular; our work was undertaken to provide a comprehensive and integrated treatment of all aspects of the modern permanent magnet and its application.

We hope to help promote understanding and utilization of the permanent magnet on a sound engineering basis, a position not yet attained. Our treatment of the subject ranges from basic principles, concepts, and behavior to practice, all aspects of which must be understood before one can intelligently apply these materials. The task is difficult because there are many misconceptions of magnet behavior which have persisted for many years. This situation is partially caused by a tendency to ascribe to all permanent magnet materials the properties found in the widely used few. The literature on the subject is generally fragmentary and discontinuous and is not very helpful in clarifying actual conditions. Using our own experiences and the reliable experiences of many workers in the field as a base, we treat in detail controversial and poorly understood subjects like the determination of leakage, the basis for the proper comparison of different permanent magnet materials, the utilization of high coercive force materials, and the stability of permanent magnets.

We are hopeful that our work allows the reader who has a specific permanent magnet problem confidently to seek a solution based on the knowledge that magnet performance is fully predictable according to physical laws under any environmental conditions likely to be encountered. If our book serves to bridge the many obvious voids in the literature between the description of unit magnetic properties and the final magnet configuration most economically filling the required specification, we shall consider it progress. We also hope that others will organize and report their experiences in this field to assist further in the intelligent application of these materials.

Our book is primarily directed toward the engineer concerned with application of the permanent magnet; it will also be helpful to engineering students who otherwise may have little opportunity to study the behavior and utilization of magnets. Finally, to those engaged in research for new materials, it will be a guide to properties that are most desirable in new materials, from the standpoint of application.

We are indebted to many of our colleagues and the companies producing permanent magnet materials, Indiana Steel Products, a division of Indiana General Corporation, Arnold Engineering Company, a division of Allegheny Ludlum, Crucible Steel Company, and the General Electric Company, for permission to use their material. We are especially grateful to Professor E. N. de C. Andraide for permission to use his early history.

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chapter one

The Early History of the Permanent Magnet

The history of magnetism has been but little explored, and it is not at all generally known how powerful were the magnets produced more than two centuries ago or what methods were used for their production. It will be a surprise to many, too, that permanent magnets made from powdered iron oxide—supposedly a quite recent invention—were known in the eighteenth century. This article traces the history of permanent magnets from ancient times up to the invention of the Heusler alloys at the beginning of the present century.

The manufacture of permanent magnets is today a flourishing activity, at once a science and an art, especially at Sheffield. This may cause some surprise, since there appears to be a widespread impression that such magnets have, for all important purposes, been superseded by the electromagnet. However, the permanent magnet plays an essential part in high-tension magnetos, in telephone generators, in telephone receivers, in gramophone pick-up units, in moving-coil loudspeakers, in television focus units and other equipment involving deflection of electron beams, in electricity meters, and in thermostats. It is essential also in many less familiar devices, such as permanent-magnet chucks and magnetic separators, designed to remove unwanted ferruginous particles. Much admirable research and much ingenuity

A most interesting and detailed history of the permanent magnet appeared in *Endeavour,* Volume XVII, Number **65**, January **1958**. Entitled, "The early history of the permanent magnet," it was prepared by Professor E. N. da C. Andrade of the Imperial College of Science and Technology-University of London. Professor Andrade has kindly granted permission to reprint this article as an introduction to this treatment of the permanent magnet.

have been, and are being, devoted to the special alloys now generally used, to the methods of magnetization, to shape and general design, including that of soft-iron pole-pieces, and to other highly specialized problems. Even in the field of atomic physics the permanent magnet may be found. On account of the constancy of its field, C. D. Ellis used such a magnet for work on β-ray spectra, the strength being changed by currents applied between the experiments. Large permanent magnets have been used in cosmic ray research and in radiofrequency spectroscopy. In a recent book P. R. Bardell (1) gives a table of some applications of permanent magnets notable for the variety it exhibits.

All these uses belong substantially to the present century—in fact the main developments of the permanent magnet as now known are matters of the last thirty years. In the early days of physics, however, the permanent magnet was the subject of much attention and research, especially before the electromagnet was developed and electric current supply became general. In the histories of physics the pioneering work of William Gilbert on magnetism is recorded, but the interest in the permanent magnet of such men as Canton, Aepinus, Coulomb, and Jamin, cited for other achievements, is neglected, and so are many very interesting achievements of less famous men. Some account will here be given of work up to the end of the nineteenth century, which sees the close of an epoch.

The only permanent magnet known to the ancients was the loadstone or lodestone (literally, "way stone," from its guiding the mariner on his way; cf. lodestar). This is a variety of magnetite, Fe_3O_4, which as found in the natural state is magnetic. It received its classical name *magnes* because it was found in Magnesia, a district in Thessaly. Thales of Miletus (circa 600 B.C.) is said to have known of its abnormal properties, and its attractive powers are mentioned by various of the great Greek philosophers of the period 400 to 200 B.C. Later Lucretius, in *De natura rerum* (vi, 1042), records repulsion, without any very precise notion of what was in question—"Sometimes too it happens that the nature of iron is repelled from this stone, being in the habit of flying from and following it in turns."

The first artificial permanent magnets were iron needles which had been "touched" by a loadstone. Much has been written as to when and where the process originated. Round about 1200 the French troubadour Guyot de Provins (whom E. Hoppe [2] calls Hugue de Bercy) records in his satirical poem *La Bible* a compass made of such a touched needle supported by a floating straw. Peter Peregrinus in his famous *Epistola ad Sygerum de Foucaucourt militem de magnete,* 1269, wrote that it was known to all who had tried it that an oblong piece of iron which a loadstone had touched turned towards the pole if floated on a piece of wood. Robert Norman in his little book *The Newe Attractive,* 1581, likewise speaks of his needles as touched with the stone, but gives no particulars. There are Chinese claims, too, but our concern here is the development of the permanent magnet, as it can be continuously followed, and these few words of reference are intended to do no more than to indicate dates of general knowledge.

The first great systematic work on the magnet is that described by William Gilbert (sometimes spelt Gilberd by contemporaries) in the famous *De Magnete Magneticisque Corporibus et de Magno Magnete Tellure Physiologia Nova,* published in 1600. This is one of the great classics of experimental physics, and its value was at once recognized by, for instance, Galileo, who wrote (3): "I extremely praise, admire and envy this author for that a conceit so stupendous should come into his mind, touching a thing handled by infinite sublime wits and hit upon by none of them." In an age when much that was written about the magnet was worthless tradition and absurd, if amusing, superstition Gilbert stands out as a most careful and critical experimenter. Characteristically, he tells the reader "Let whosoever would make the same experiments handle the bodies not heedlessly and clumsily but carefully, skilfully and deftly; when an experiment fails he should not ignorantly doubt our discoveries, for there is naught in these books that has not been investigated and done again and again by us." An example of the traditional beliefs refuted by Gilbert is that the loadstone lost its attractive power in the presence of, among various other things (including garlic and goats' blood), the diamond: he showed that surrounding the stone with seventy-five diamonds had no effect. Some of his most important work was on terrestrial magnetism, which does not here concern us; but he also carried out fundamental investigations on the magnet itself.

The most powerful magnets of Gilbert's time were still loadstones. He described how to make them more powerful attractors of iron by "arming" them, that is, by attaching soft iron caps at each end, as shown in Figure 1-1. This is the first example of the soft iron pole-pieces used in many cases with modern permanent magnets. With a particular stone, Gilbert writes that arming increased the weight of iron that could be lifted from 4 ounces to 20 ounces; but he is careful to state that arming does not increase the attraction at a distance.

Figure 1-1. Gilbert's capped or "armed" loadstones, as represented in the *De Magnete.*

Gilbert was much concerned with making permanent magnets, or artificial magnets as they were long called to distinguish them from the natural loadstone. He needed these for compasses and dip circles, and called such pivoted needles *versoria,* which we may translate "turnabouts," the word *versorium* being apparently of his invention. He lays stress on the material to be used: at one place he says that the needles are to be made *ex optimo aciario,* which would seem to mean of the best edge-steel, the word, not classical Latin, being derived from *acies,* an edge, in particular a sword edge (cf. French *acier*). Elsewhere he specifies "the best iron which has been melted down" (*ferrum excoctum*) or "iron made hard," so that he clearly meant to warn against the use of soft iron. As regards the size of his magnets, he said that his dip circle, shown in Figure 1-2, might be 10 to 12 inches across, and he speaks elsewhere of a magnet as thick as a goose quill and about 8 inches long.

Gilbert gives three ways by which permanent magnetism (or "verticity" as he termed it) may be given to steel. The first method was by touch with a single loadstone, which was to be drawn from the middle of the needle to the end, where the application was to be continued by a very gentle rubbing. In discussing the dip needle he speaks of touching the opposite ends with the two different poles of the loadstone, but he never deals with anything but single touch. The second method was forging with the horizontal specimen pointing north and south in the Earth's field, as shown in Figure 1-3. He also recorded that iron wires become magnetic if drawn in a north–south direction, but not if drawn in an east–west direction. This second method, then, was one of considerable plastic deformation in the Earth's field.

Gilbert was quite clear that a red heat destroyed permanent magnetism, but records that a red-hot iron bar left to cool in the direction of the Earth's field became permanently magnetic, and further that

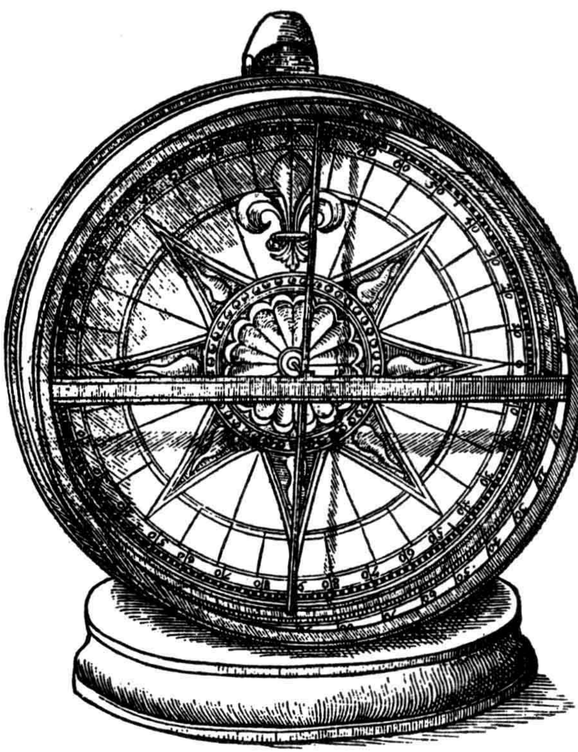

Figure 1-2. Gilbert's dip circle, as represented in the *De Magnete.*

Figure 1-3. Smoothing an iron rod in the direction of the Earth's field, as shown in Gilbert's *De Magnete*. (Septentrio, north; auster, south.)

unheated iron bars left in the direction of the Earth's field for twenty or more years—such as window bars—likewise acquired verticity. This magnetization by long exposure to the Earth's field without plastic deformation constitutes a third procedure, and these three general methods cover all that were used until the electromagnet was introduced in 1825. If J. Robison's (4) words in 1822, "It is not saying too much of this work of Dr. Gilbert's to affirm, that it contains almost everything that we know about magnetism," were an exaggeration, they were not a very great exaggeration.

Not much advance was made in the seventeenth century. The method of arming loadstones was improved by squaring the ends and applying suitably shaped iron plates, as illustrated in Figure 1-4, which increased the attractive force on iron in contact. A typical mounted loadstone of the seventeenth century is shown in Figure 1-5. Boyle, in 1675, shrewdly observed that the destruction of magnetism by heat without any apparent change in the metal showed that magnetism was a matter of the "disposition or internal constitution" of the iron, and, in confirmation of Gilbert's general discovery, said that iron fire tongs and such-like that were heated and stood upright—which means

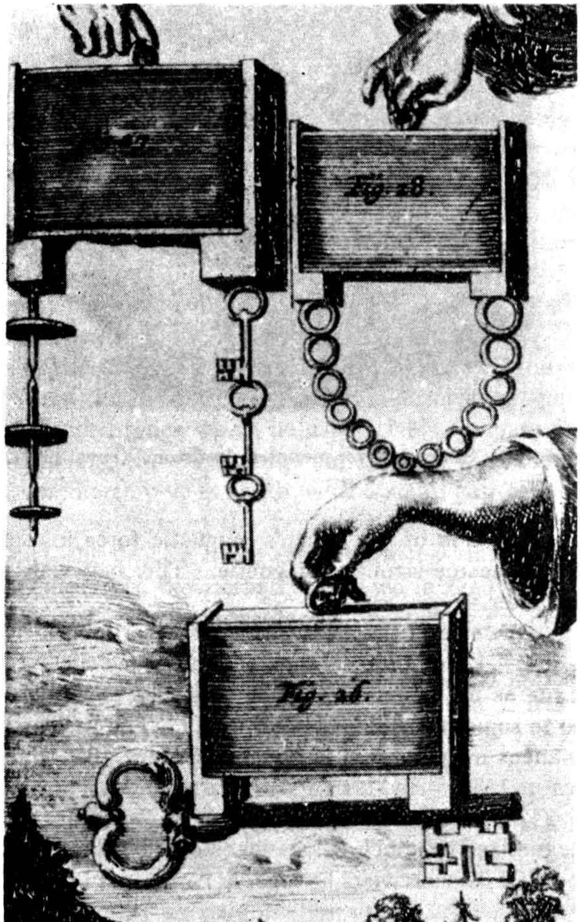

Figure 1-4. Armed loadstones as represented by Dalence in his *Traitte de l'Aiman*, 1687.

Figure 1-5. Stewart silver-mounted loadstone (circa 1660).

nearly in the direction of the Earth's magnetic force in England—to cool sometimes became strongly magnetic. This fact was, as will be seen, applied later.

It must be remembered that loadstones were very expensive. Hartsoeker (5), in 1711, complained that he was asked 3000 guilders for one half as big as his fist, a sum which was then equivalent to about £250, and so to something like £3000 of today. The first man to make strong permanent magnets was Servington Savery (6), who described his processes in 1730. He started with wires about $\frac{1}{20}$th inch in diameter and $2\frac{3}{4}$ inches long, of steel which he "seasoned very hard." These he magnetized by touch with a loadstone, but he gives no details as to method. Of 37 such wires he made a hexagonal bundle, like poles to like, to which he fitted soft iron endpieces or armatures. This was the first compound magnet, made up of smaller ones. With two of these he magnetized steel wires by the method, invented by him, of divided touch, placing the north pole of one magnet and the south pole of the second magnet close together at the middle of the rod to be magnetized and drawing them apart. He also adopted a method, later used by others, of placing several of the stout wires to be magnetized end to end in a groove and treating them as one, rejecting the end ones. A single one of his wires would lift a nail twelve times its own weight. Savery also made, by a complicated method of mutual touches, large bar magnets, 16 x ¾ x ¾ inch, one of which would sustain another when placed end to end. It must be remembered that the lifting power of geometrically similar magnets varies, *ceteris paribus*, approximately as the ⅔rd power of the weight.

Savery was followed by a man who made a European reputation with his magnets, Gowin Knight (1713–72). The spelling of his name gave his French contemporaries much trouble, the extreme version being the Gnith of Sigaud de la Fond: Coulomb calls him Knigth. He carried out a flourishing business—or, to use the language of a politer day, "procured considerable pecuniary advantages"—with these magnets: Benjamin Wilson (7) speaks of "two of his best ten guinea bars." It may be noted that as the first principal librarian at the British Museum his salary was £160 a year.

Knight kept secret many of his methods, including the way in which he magnetized his initial bars. He did, however, communicate a method of divided touch which he used for his compass needles, which were 5 inches long (8). Two large bar magnets of hardened steel were placed in line, north pole to south, with a small gap between them; the needle was pressed on to the two ends and the magnets were then drawn apart, the process being repeated a few times. George Adams (9) in 1794 described the method illustrated in Figure 1-6, in which the ends of the bar to be magnetized are supported by permanent magnets, and the method of divided touch, with inclined magnets, is employed. The inclined magnets are placed together, north pole to south, as

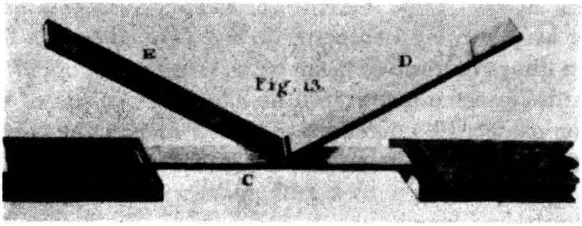

Figure 1-6. George Adams's representation of one of Gowin Knight's methods of magnetization.