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PERMANENT MAGNET STEEL

The National Bureau of Standards receives numerous inquiries regarding permanent magnets and the materials from which they are made. The following summary of the general principles involved in the manufacture and use of permanent magnets has been prepared in the hope that it will give the information requested in the majority of these inquiries. The information has been collected from several sources including text books, technical publications, informal reports from other laboratories, and unpublished data obtained at this Bureau. Since the actual results to be obtained from any given material depend on many different factors, it is neither feasible nor desirable to present specific data.

Properties required of permanent magnets. The function of a permanent magnet is to maintain a magnetic field of a certain intensity in a definite space. For many applications it is essential that the intensity of this field shall remain constant over a long period of time. It is also generally desirable that the size of the magnet be as small as possible. When a ferromagnetic material is magnetized by subjecting it to the influence of a magnetizing force such as is produced within a solenoid or between the poles of an electromagnet, the degree of magnetization is expressed in terms of the "number of lines of force per square centimeter of area" which is technically called the magnetic induction and designated by the symbol B. The magnetizing force is designated by the symbol H. When the magnetizing force is removed, a certain amount of the induction remains in the material and is called the residual induction B_r. The induction can be reduced in value by the application of a magnetizing force in the opposite direction. The value of the reversed magnetizing force required to reduce the induction to zero is called the coercive force H_c and is a measure of the resistance of the material to demagnetization. In order to make a good permanent magnet, a material should have high values of B_r and H_c.

Materials for permanent magnets. Although many kinds of steel have magnetic properties such that fairly good permanent magnets can be made from them, the best results are obtained by the use of steels or alloys manufactured especially for the purpose. Such materials, when subjected to the proper heat treatment, possess the desirable magnetic properties. Individual manufacturers generally market their products under brand names but they can

also be classified in terms of the principal alloying elements.

The principal types of magnet steel are listed in the following table which gives representative values of B_r, H_c, and $(B_d H_d)_{max}$. The latter figure is the maximum value of the product of corresponding values of B_d and H_d (the coordinates of points on the hysteresis loop between B_r and H_c), and is sometimes called the energy-product as it is proportional to the maximum amount of magnetic energy that can be stored by a magnet. The energy-product may be considered as an index of magnetic quality. The values given in the table are to be taken only as an indication of the order of magnitude to be expected from the various types of steel. The actual values obtained vary through rather wide limits as the result of differences in composition and heat treatment.

Type	B_r	H_c	$(B_dH_d)_{max}$
Tungsten	9500	60	240,000
Chromium	10500	55	230,000
17% Co	10000	125	520,000
35% Co	9500	210	840,000
Al-Ni	7500	400	1,260,000
Al-Ni-Co	6000	600	1,500,000
Co-Ni-Ti	7000	900	2,650,000

All magnet steels of the types listed contain iron as the principal constituent. The proportions of the principal alloying elements vary, and certain minor constituents are always present. The tungsten and chromium steels are generally hardened by quenching from suitable temperatures in water although oil is sometimes used for chromium steels of high chromium content. The 35% cobalt type is quenched in oil. For the 17% cobalt type a rather complicated treatment is required in order to bring out the best qualities.

The aluminum-nickel, aluminum-nickel-cobalt, and cobalt-nickel-titanium types are known as "precipitation-hardening" steels. They are first heated to a very high temperature in order to dissolve certain constituents and are then either cooled rapidly in air or quenched. They are subsequently reheated to cause precipitation of the dissolved constituents and finally cooled to room temperature. The final properties depend both upon the temperature and time of holding at this temperature. Magnet steels of the precipitation-hardening type must be cast to shape as they can not be forged or machined.

The correct heat treatment for hardening a given steel depends primarily upon its chemical composition. Furthermore, the final result is affected by preliminary treatments such as annealing or forging. Unsatisfactory results generally follow from improper heat treatment, even though the steel may be initially of good quality. For this reason instructions for heat treating should always be obtained from the manufacturer and carefully followed.

Permanence and "Aging" of Magnets. The degree of permanence of a magnet depends upon its ability to withstand the deteriorating effects of time, temperature, mechanical shock or vibration, and external magnetic fields.

In steels which are hardened by quenching, the sudden cooling suppresses certain structural transformations which would occur at fairly high temperatures in the ordinary course of cooling, and which tend to proceed to a certain extent over considerable periods of time even at room temperature. This gradual change is termed aging and may result in a reduction of from 10 to 20 percent in magnetic strength during the course of a year. The change takes place rapidly at first and less rapidly as time goes on. The approach toward a stable state can be greatly accelerated by artificial aging or maturing. This consists in heating the magnet to the temperature of boiling water (100°C) and maintaining it at that temperature for several hours. Twenty-four hours is generally sufficient. This procedure is sometimes modified by subjecting the magnet to alternate heating and cooling. The continuous heating, however, appears to be fully as effective.

The effect of temperature on a finished magnet depends upon the type of steel of which it is made. Magnets made of steels hardened by quenching can not be heated to temperatures much above 100°C without seriously impairing their properties. The precipitation-hardening steels, on the other hand, can withstand the influence of much higher temperatures. Since the final treatment of these steels consists in heating them to a temperature of at least 600°C and since no suppression of transformations is involved the structure is inherently more stable. It is known that the magnetic properties of these steels are not seriously affected by temperatures which would completely ruin magnets made from steels hardened by quenching.

Mechanical shock or vibration tends to decrease the strength of a freshly magnetized magnet. This is a purely magnetic phenomenon and does not involve any structural change. If the shocks are oft repeated or the vibration is continued for a sufficient length of time, the magnet finally reaches a condition such that further shocks or vibration produce no appreciable effect. The process of stabilization therefore should include a certain amount of vibration or shocks. Susceptibility to the effect of shock or vibration appears to be a function of the coercive force of the steel. The higher the coercive force the less the effect. The effect is said to be practically negligible in the precipitation-hardening steels.

The effect of an external magnetic field may be either permanent or temporary according as the field is greater or less than a certain critical value. Magnets can be stabilized against the influence of external fields by partial demagnetization. Practice varies as to the amount of demagnetization but a reduction of from 10 to 20 percent is customary. If this is done the effect of an external field not exceeding that used for demagnetization is not permanent but persists only so long as the field is acting.

Artificial aging, vibration, and partial demagnetization are required only when the magnet must maintain a constant strength as is necessary, for instance, in electrical measuring instruments. For many applications these treatments can be dispensed with.

To sum up briefly, in order to obtain a good permanent magnet of the highest degree of constancy, the following points are essential: (a) a good grade of magnet steel, (b) proper heat treatment, (c) artificial aging (except possibly in the case of the precipitation-hardening alloys), (d) stabilization against mechanical shocks or vibration, and (e) partial demagnetization.

References for additional information. For the benefit of the inquirer who desires more detailed or specific information and who has access to a technical library, the following references are recommended.

S. P. Thompson in an article, "Magnetism of Permanent Magnets", published in the Journal of the Institution of Electrical Engineers (British), Vol. 50, p.80, 1913, gives an excellent review of the information available up to the time the article was published, together with a very complete bibliography. Also, see "Permanent Magnets" by F. C. Kelly in the General Electric Review, Vol. 20, p. 569, 1917.

Honda and Saito in the Physical Review, Vol. 16, p. 495, 1920, in an article, "K S Magnet Steel", announce the development of the cobalt type of magnet steel and give some of its properties.

Further information on the cobalt steels is given in "Cobalt Magnet Steel" by Brace in the Electric Journal, Vol. 26, p. 111, 1929 and "Some Principles Governing the Choice and Utilization of Permanent Magnet Steels" by Sanford, Scientific Papers of the Bureau of Standards, Vol. 22, p. 557 (SP No. 567), 1927.

An article by Pölzguter on "Recent Developments in Alloys for Permanent Magnets" is reviewed on page 77 of the October 1935 number of the Metallurgist. This gives an account of the newer types of alloys.

An article entitled "Permanent Magnet Materials" by C. S. Williams, Electrical Engineering, Vol. 55, p. 19, Jan. 1936, gives information about several types of magnet steel.

For the inquirer who can read German, a good summary of the properties of permanent magnet alloys is given by Honda in Metallwirtschaft, Vol. 13, p. 425, 1934.

A book by Spooner entitled "Properties and Testing of Magnetic Materials" published by the McGraw-Hill Book Company, New York, has a chapter on Permanent Magnet Steels.

In all of the references given will be found further lists of publications on the subject.