Factors Affecting Magnetic Quality*

By R. M. BOZORTH

IN THE preparation of magnetic materials for practical use it is important to know how to obtain products of the best quality and uniformity. In the scientific study of magnetism the goal is to understand the relation between the structure and composition on the one hand and the magnetic properties on the other. From both standpoints it is necessary to know the principal factors which influence magnetic behavior. These are briefly reviewed here.

The properties depend on chemical composition, fabrication and heat-treatment. Some properties, such as saturation magnetization, change only slowly with chemical composition and are usually unaffected by fabrication or heat treatment. On the contrary, permeability, coercive force and hysteresis loss are highly sensitive and show changes which are extreme among all the physical properties. Properties may thus be divided into *structure-sensitive* and *structure-insensitive* groups. As an example, Fig. 1 shows magnetization curves of permalloy after it has been (a) cold rolled, (b) annealed and cooled slowly, and (c) annealed and cooled rapidly. The maximum permeability varies with the treatment over a range of about 20 fold, while the saturation induction is the same within a few per cent. Structure sensitive properties such as permeability depend on small irregularities in atomic spacings, which have little effect on properties such as saturation induction.

Some of the more common sensitive and insensitive properties are listed in Table I. The principal physical and chemical factors which affect these properties are listed in column 3. Their various effects will now be briefly discussed and illustrated.

Phase Diagram

Some of the most drastic changes in properties occur when the fabrication or heat treatment has brought about a change in structure of the material. For this reason the phase diagram or constitutional diagram is of the utmost importance in relation to the preparation and properties of magnetic materials. As an example consider the phase diagram of the binary iron-cobalt alloys of Fig. 2. Here the various areas show the phases, of different

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*This article is the substance of Chapter II of a book entitled "Ferromagnetism" to be published early in 1951 by D. Van Nostrand Company, Inc.

composition or structure, which are stable at the temperatures and compositions indicated. The α phase has the body-centered-cubic crystal structure characteristic of iron. At 910°C it transforms into the face-centered phase γ, and at 1400° into the δ phase, which has the same structure as the α phase. At about 400°C cobalt transforms, on heating, from the ϵ phase (hexagonal structure) into the γ phase.

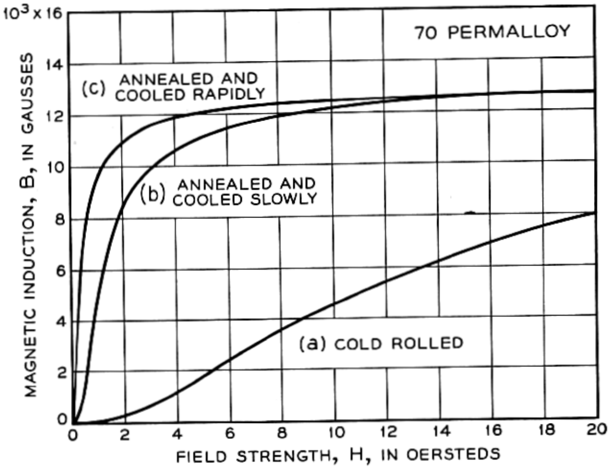

Fig. 1—Effect of mechanical and heat treatment on the magnetization curve of 70 permalloy (70% Ni, 30% Fe).

TABLE I

Properties Commonly Sensitive or Insensitive to Small Changes in Structure, and Some of the Factors which Effect Such Changes

Structure-Insensitive Properties	Structure-Sensitive Properties	Factors Affecting the Properties
I_s, Saturation Magnetization θ, Curie Point λ_s, Magnetostriction at Saturation K, Crystal Anisotropy Constant	μ, Permeability H_c Coercive Force W_h Hysteresis Loss	Composition (gross) Impurities Strain Temperature Crystal Structure Crystal Orientation

The dotted lines indicate the Curie point, at which the material becomes non-magnetic.

In between the areas corresponding to the single phases α, γ, δ and ϵ there are two-phase regions in which two crystal structures co-exist, some of the crystal grains having one structure and others the other. Such a two-phase structure is usually evident upon microscopic or X-ray examina-

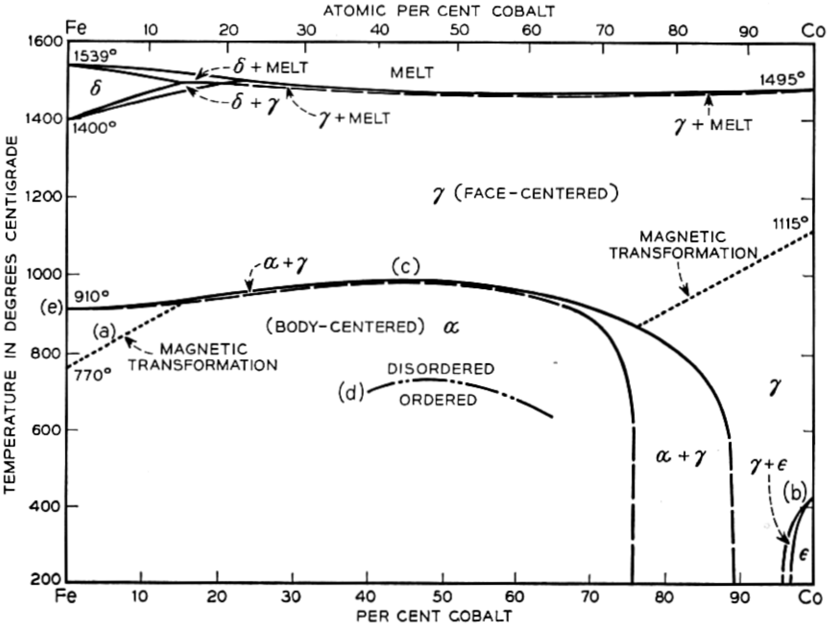

Fig. 2—Phase diagram of iron-cobalt alloys.

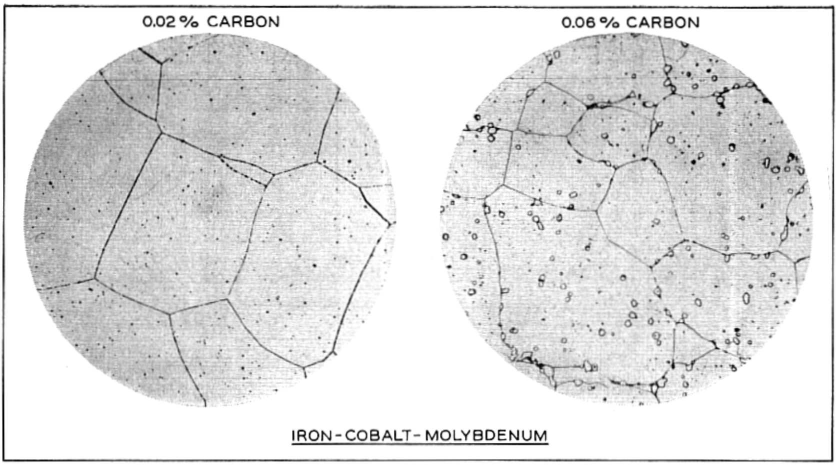

Fig. 3—Photomicrographs of remalloy (12% Co, 17% Mo, 71% Fe) showing the precipitation of a second phase in the specimen containing an excess of carbon (0.06%) Courtesy of E. E. Thomas. Magnification: (a) 50 times, (b) 200 times.

tion. Microphotographs of a single-phase alloy and a two-phase alloy of iron-cobalt-molybdenum are reproduced in Fig. 3 (a) and (b).

The diagram of Fig. 2 shows several kinds of changes that affect the magnetic properties. At (a) the material becomes non-magnetic on heating, without change in phase. At (b) there is a change of phase, both phases being magnetic. Figure 4 shows the changes in magnetic properties that occur during this latter transition; they are due partly to the high local strains that result from the change in structure, and partly to the difference in the crystal structures of the two phases. At (c) there is a change from a ferromagnetic to a non-magnetic phase, and Fig. 5 shows the rapid change in magnetization that occurs when the temperature rises in this area. At

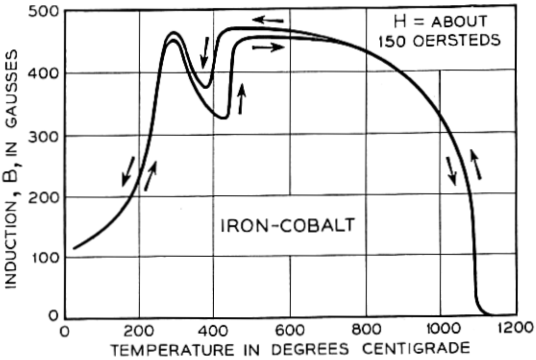

Fig. 4—Effect of phase transformation of cobalt on magnetization with a constant field of 150 oersteds. Both phases magnetic. *Masumoto.*

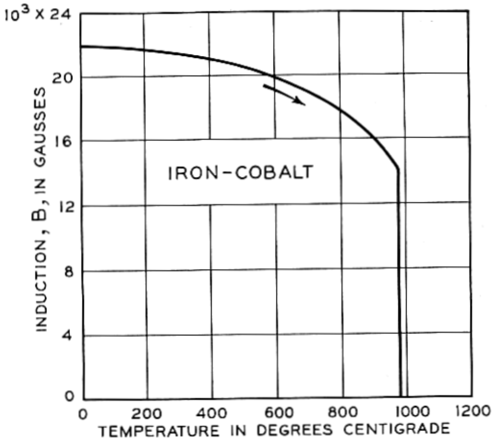

Fig. 5—Phase transformation in iron-cobalt alloy (50% Co). High-temperature phase is non-magnetic.

(d) the α phase becomes ordered on cooling, i.e., the iron and cobalt atoms tend to distribute themselves regularly among the various atom positions so that each atom is surrounded by atoms of the other kind. This phenomenon is especially important in connection with the properties of iron-aluminum and manganese-nickel alloys.

The transition at (e) is entirely in the non-magnetic region but it has its influence on the properties of iron at room temperature. If iron is cooled very slowly through (e), the internal strains caused by the change in structure will be relieved by diffusion of the metal atoms, but if the cooling is too rapid there will not be sufficient time for strain relief. Practically this means that to obtain high permeability in iron it must be annealed for some time below 900°C, or cooled slowly through this temperature so that diffusion will have time to occur. In most ferromagnetic materials diffusion occurs at a reasonably rapid rate only at temperatures above about 500 to 600°C.

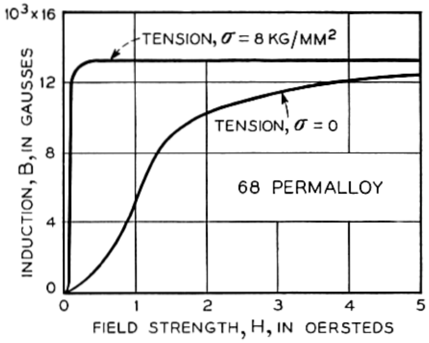

Fig. 6—Effect of tension on the magnetization curve of 68 permalloy.

The effect of a homogeneous *strain* on the magnetization curve can be observed in a simple way, as by applying tension to an annealed wire and then measuring B and H. The effect of tension on some materials is to increase the permeability and on other materials to decrease it, as shown in Fig. 6. Compression usually causes a change in the opposite sense.

The internal strains resulting from *plastic deformation* of the material, brought about by stressing beyond the elastic limit, as by pulling, rolling or drawing, almost always reduce the permeability. The material is then under rather severe local strains similar to those present after phase change, and these strains are different in magnitude and direction in different places in the material and have quite different values at points close together. Strains of this kind can usually be relieved by annealing; therefore, metal that has been fabricated by plastic deformation is customarily annealed to raise its permeability. Figure 1 shows the effect of annealing a permalloy strip that has been cold-rolled to 15 per cent of its original thickness.

The *temperature* also is effective in changing permeability and other properties, even when no change in phase occurs. Figure 7 shows the rapidity with which the initial permeability decreases as the Curie point is approached. For this material, Ferroxcube III, a zinc manganese ferrite ($ZnMnFe_4O_8$), the Curie point is not far above room temperature.

The effect of *impurities* may be illustrated by the B vs H curves for iron containing various amounts of carbon. Curve (a) of Fig. 8 is for a mild steel having 0.2 per cent carbon, (b) is for the iron commonly used in electromagnetic apparatus—it contains about 0.02 per cent carbon and is annealed at about 900°C. When this same iron is purified by heating for several hours at 1400°C in hydrogen, the carbon is reduced to less than 0.001 per cent and other impurities are removed, and curve (c) is obtained.

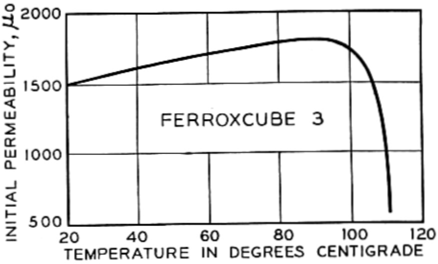

Fig. 7—Variation of initial permeability of Ferroxcube 3, showing maximum at temperature just below the Curie temperature.

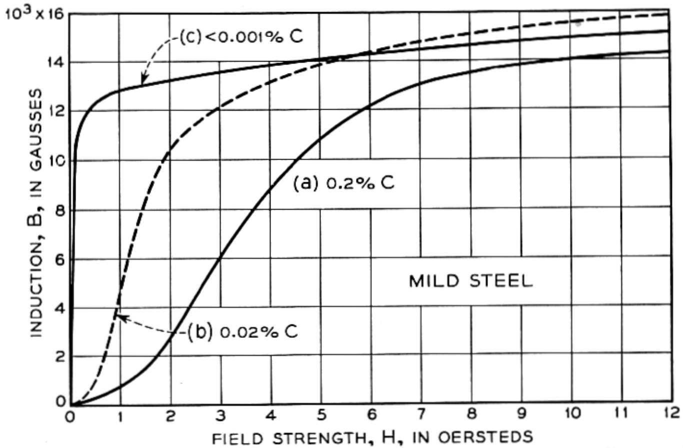

Fig. 8—Effect of impurities on magnetic properties of iron. Annealing at 1400°C in hydrogen reduces the carbon content from about 0.02 per cent to less than 0.001 per cent.

Finally, Fig. 9 shows that large differences in permeability may be found by simply varying the *direction of measurement* of the magnetic properties in a single specimen. The material is a single crystal of iron containing about 4 per cent silicon, and the directions in which the properties are measured are [100] (parallel to one of the crystal axes), and [111] (as far removed as possible from an axis). The magnetic properties in the two directions are different because different "views" of the atomic arrangement are obtained in the two directions.

PRODUCTION OF MAGNETIC MATERIALS

In the preparation of magnetic materials for either laboratory or commercial use there are many processes which influence the chemical and physical structure of the product. The selection of raw materials, the melting and casting, the fabrication and the heat treatment, are all important and must be carried out with a proper knowledge of the metallurgy of the material. A brief description of the common practices is now given. For further discussion the reader is referred to more detailed metallurgical books and articles.

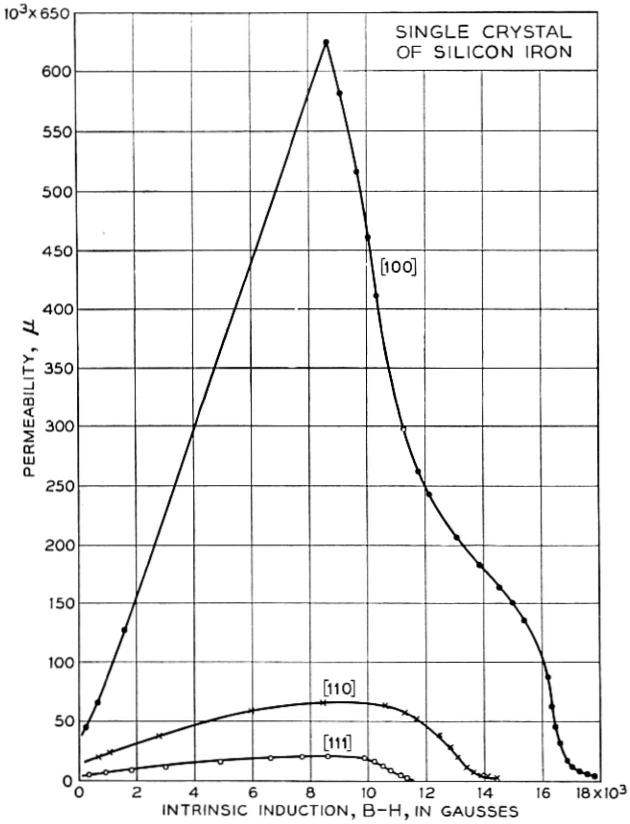

Fig. 9—Dependence of permeability on crystallographic direction. *Williams.*

Melting and Casting

For experimental investigation of magnetic materials in the laboratory, the raw materials easily obtainable on the market are generally satisfactory. When high purity is desirable specially prepared materials and crucibles must be used and the atmosphere in contact with the melt must be controlled. The impurities that have the greatest influence on the magnetic properties of high permeability materials are the non-metallic elements, particularly oxygen, carbon and sulfur, and the presence of these impurities is therefore watched carefully and their analyses are carried out with special accuracy. Impurities are likely to change in important respects during the melting and pouring on account of reactions of the melt with the atmosphere, the slag or the crucible lining, or because of reactions taking place among the constituents of the metal.

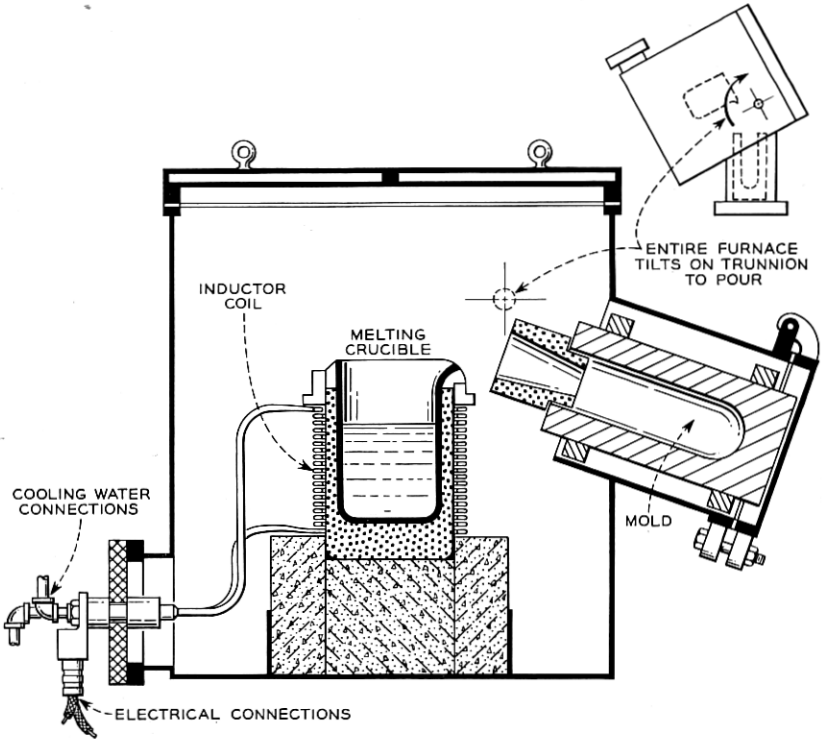

Fig. 10—Induction furnace designed for small melts in controlled atmosphere, as designed by J. H. Scaff and constructed by the Ajax Northrup Company.

Melting of small lots (10 pounds) is best carried out in a high-frequency induction furnace. Figure 10 shows such a furnace designed for melting ten to fifty pounds, and casting by tilting the furnace, the whole operation being carried out in a controlled atmosphere. High-frequency currents (usually 1,000 to 2,000 cycles/sec but sometimes much higher) are passed through the water-cooled copper coils, and the alternating magnetic field so produced heats the charge by inducing eddy currents in it. Crucibles are usually composed of alumina or magnesia.

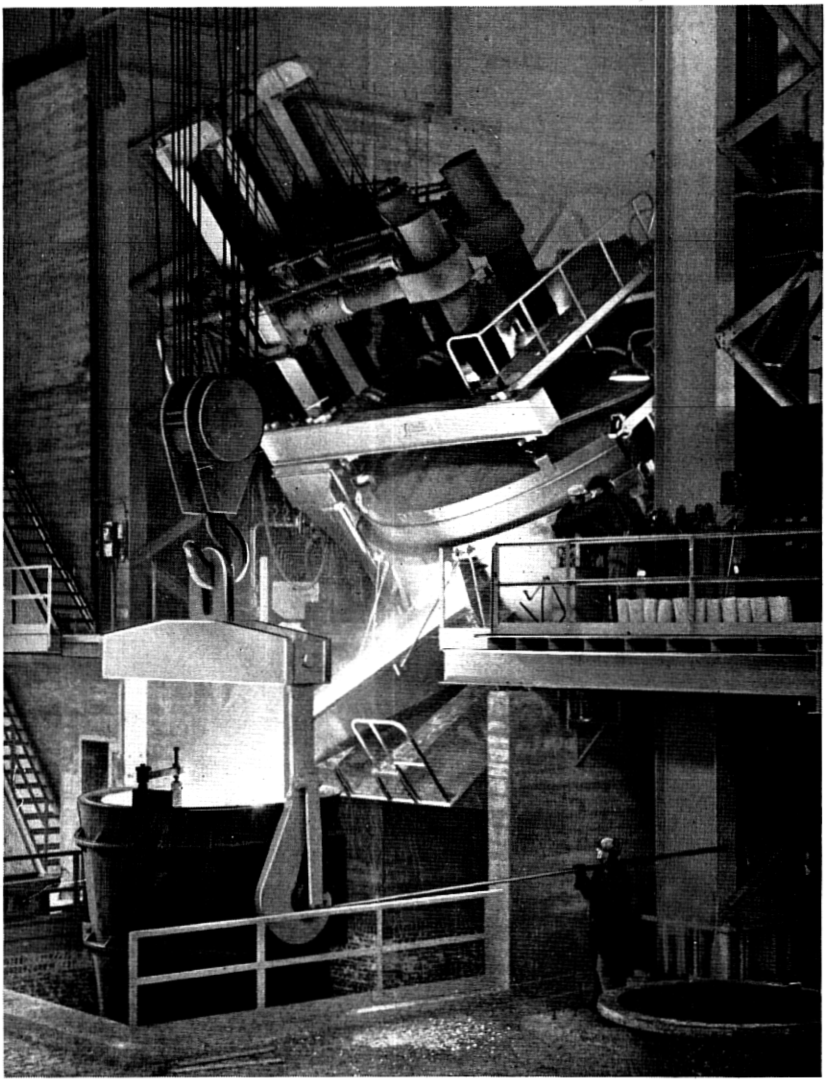

Fig. 11—Arc furnace for large commercial melts. Courtesy of J. S. Marsh of the Bethlehem Steel Company.

On a commercial scale melts of silicon-iron are usually made in the open hearth furnace, in which pig-iron and scrap are refined and ferro-silicon added. The furnace capacity may be as large as 100 tons. Sometimes silicon-iron, and usually iron-nickel alloys, are melted in the arc furnace, in amounts varying from a few tons to 50 tons. A photograph of such a furnace, in the position of pouring, is shown in Fig. 11. The heat is produced in the arc drawn between large carbon electrodes immersed in the metal, the current sometimes rising to over 10,000 amperes. By tipping the furnace the melt is poured into a ladle, and from this it is poured into cast-iron molds through a valve-controlled hole in the ladle bottom. Special-purpose alloys, including permanent magnets, are prepared commercially in high-frequency induction furnaces or in arc furnaces in quantities ranging from a fraction of a ton to several tons.

TABLE II

Heats of Formation and Other Properties of Some Oxides (*Sachs and Van Horn*[4])

Oxide	Heat of formation (Kilo-cal per gram atom of metal)	Melting Point (°C)	Density (g/cm³)
CaO	152	>2500	3.4
BeO	144	>2500	3.0
MgO	144	2800	3.65
Li_2O	141	>1700	2.0
Al_2O_3	127	2050	3.5
V_2O_2	116	1970	4.9
TiO_2	109	1640	4.3
Na_2O	101	*	2.3
SiO_2	95	1670	2.3
B_2O_3	94	580	1.8
MnO	91	1650	5.5
ZrO_2	89	2700	5.5
ZnO	85	*	5.5
P_2O_5	73	*	2.4
SnO_2	68	1130	6.95
FeO	66	1420	5.7
NiO	58	**	7.45

* Sublimes.
** Decomposes before melting.

Slags are commonly used when melting in air, both to protect from oxidation and to reduce the amounts of undesirable impurities. Common protective coverings are mixtures of lime, magnesia, silica, fluorite, alumina, and borax in varying proportions. In commercial production different slags are used at different stages, to refine the melt; e.g., iron oxide may be used to decarburize and basic oxides to desulfurize.

Melting in vacuum requires special technique that has been described in some detail by Yensen.[1] Commercial use has been described by Rohn[2] and others.[3] Melting in hydrogen has been used on an experimental scale in both

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[1] T. D. Yensen, *Trans. A.I.E.E.* 34, 2601–41 (1915).
[2] W. Rohn, Heraeus Vacuumschmelze, Albertis, Hanau, 356–80 (1933).
[3] W. Hessenbruch and K. Schichtel, *Zeits. f. Metallkunde* 36, 127–30 (1944).

high-frequency and resistance-wound furnaces. In commercial furnaces Rohn has used hydrogen and vacuum alternately before pouring, for purification in the melt, in low-frequency induction furnaces having capacities of several tons.

Just before casting a melt of a high-permeability alloy such as iron nickel, a deoxidizer may be added, e.g. aluminum, magnesium, calcium or silicon, in an amount averaging around 0.1 per cent. The efficacy of a deoxidizer is measured by its heat of formation, and this is given for the common elements in Table II, taken from Sachs and Van Horn.[4] Also several tenths of a per cent of manganese may be put in to counteract the sulfur so that the material may be more readily worked; the manganese sulfide so formed collects into small globular masses which do not interfere seriously with the magnetic or mechanical properties of most materials.

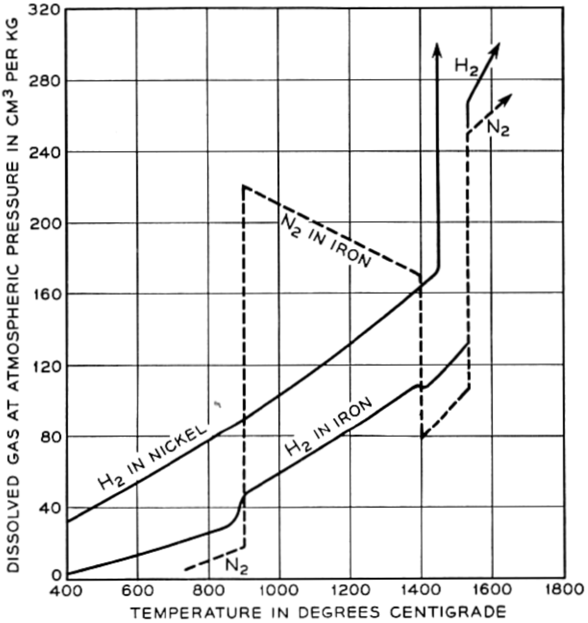

Fig. 12—Solubility of some gases in iron and nickel at various temperatures. *Sieverts.*

Ordinarily a quantity of gas is dissolved in molten metal, and this is likely to separate during solidification and cause unsound ingots. The solubilities of some gases in iron and nickel have been determined by Sieverts[5] and others and are given in Fig. 12, adapted from the compilation by Dushman.[6] The characteristic decrease of solubility during freezing is apparent. Most

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[4] G. Sachs and K. R. Van Horn, Practical Metallurgy, Am. Soc. Metals, Cleveland (1940).

[5] A. Sieverts, *Zeits. f. Metallkunde* 21, 37–46 (1929).

[6] S. Dushman, Vacuum Technique, Wiley, New York (1949).

of the gases given off by magnetic metals during heating are formed from the impurities carbon, oxygen, nitrogen and sulfur; CO is usually given off in greatest amount from cast metal, and some N_2 and H_2 are also found. Refining of the melt is therefore of obvious advantage, and the furnace of Fig. 10 is especially useful for this purpose.

Small ingots are sometimes made by cooling in the crucible. Usually, however, ingots are poured into cast iron molds for subsequent reduction by rolling, etc.; permanent magnet or other materials are often cast in sand in shapes which require only nominal amounts of machining or grinding for use in apparatus or in testing. Special techniques are used for specific materials.

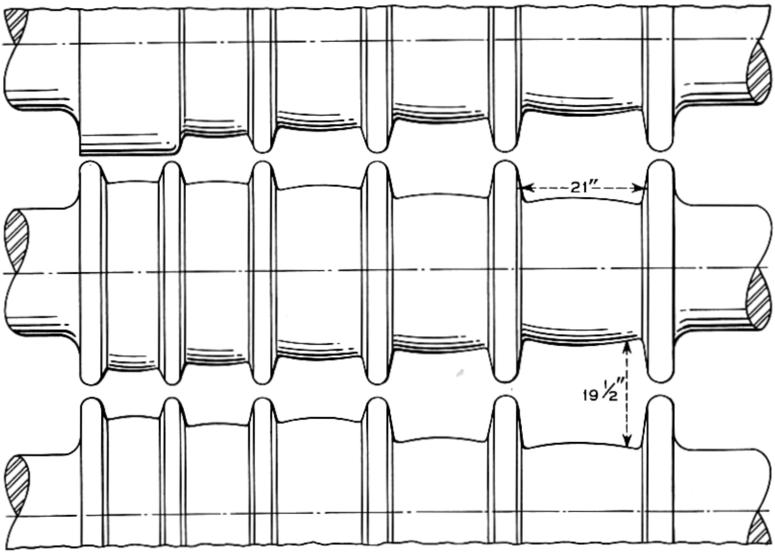

Fig. 13—Design of rolls in a blooming mill for hot reduction of ingots to rod. *Carnegie Illinois Steel Corp.*

Other considerations important in the melting and pouring of ingots are proper mixing in the melt, the temperature of pouring, mold construction, inclusions of slag, segregation, shrinkage, cracks, blow holes, etc.

Fabrication

Magnetic materials require a wide variety of modes of fabrication, which can best be discussed in connection with the specific materials. The methods include hot and cold rolling, forging, swaging, drawing, pulverization, electrodeposition, and numerous operations such as punching, pressing and spinning. In the commercial fabrication of ductile material it is common practice to start the reduction in a breakdown or blooming mill (Fig. 13) after heating the ingot to a high temperature (1200° to 1400°C). Large ingots, of several tons weight, are often led to the mill before they have cooled below the proper temperature. The reduction is continued as the metal cools, in a rod or flat rolling mill, depending on the desired form of the final product. When the thickness is decreased to 0.2 to 0.5 inch the material has usually cooled below the recrystallization temperature. Because of the difficulty in handling hot sheets or rod of small thickness, they are rolled at or near room temperature, with intermediate annealings if necessary to soften or to develop the proper structure. In experimental work, rod is often swaged instead of rolled.

In recent years the outstanding trends in methods of fabricating materials have been toward the construction of the multiple-roll rolling mill for rolling thin strip, and the continuous strip mill for high-speed production on a large scale. Figure 14 shows the principle of construction of a typical 4-high mill ((a) and (b)), and of two special mills ((c) and (d)). In the 20-high Rohn[7] mill and 12-high Sendzimir[8] mill the two working rolls are quite small (0.2 to one inch in diameter). These are each backed by two larger rolls and these in turn by others as indicated. In the Rohn mill (c), power is supplied to the two smallest rolls and the final bearing surfaces are at the ends of the largest rolls. In the Sendzimir mill (d) the power is supplied to the rolls of intermediate size and the bearing surfaces are distributed along the whole length of the largest rolls so that no appreciable bending of the rolls occurs. The small rolls reduce the thickness of thin stock with great efficiency, and the idling rolls permit the application of high pressure. In the Steckel mill power is used to pull the sheet through the rolls, which are usually 4-high with small working rolls.

The continuous strip mill is an arrangement of individual mills such that the strip is fed continuously from one to another and may be undergoing reduction in thickness in several mills simultaneously. Figure 15 shows a mill of this kind, used for cold reduction, with 6 individual mills in tandem.

For magnetic testing numerous forms of specimens are required for various kinds of tests; these include strips for standard tests for transformer sheet, rings or parallelograms for conventional ballistic tests, "pancakes" of thin tape spirally wound for measurement by alternating current, ellipsoids for high field measurements, and many others. The various forms are

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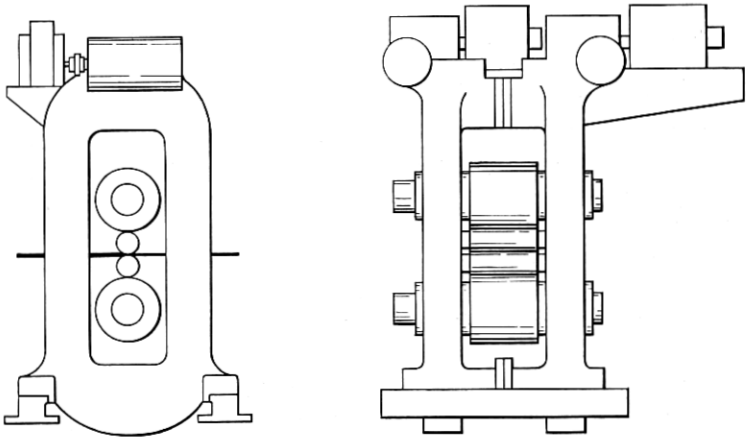
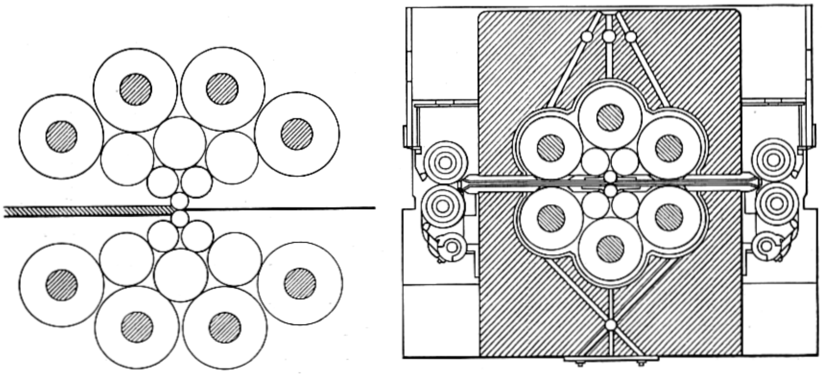
[7] W. Rohn, Heraeus Vacuumschmelze, Albertis, Hanau, 381–7 (1933).

[8] T. Sendzimir, *Iron and Steel Engr.* 23, 53–9 (1946).

required to study or eliminate the effects of eddy-currents, demagnetizing fields and directional effects and to simulate the use of material in apparatus. Most of the needs arizing in commerce and in experimental investigation are filled by strips or sheets of thicknesses from 0.002 inch to 0.1 inch from which coils can be wound or parts cut, by rods from which relay cores or other forms can be made, by powdered material used for pressing into cores for coils for inductive loading, and by castings for permanent magnets or other objects which may be machined or ground to final shape.



(a) 4-HIGH MILL, SIDE VIEW (b) 4-HIGH MILL, END VIEW



(c) 20-HIGH ROHN MILL (d) 12-HIGH SENDZIMIR MILL

Fig. 14—Arrangement of rolls in mills used for reduction of thin sheet: (a) and (b) conventional 4-high mill; (c) Rohn 20-high; (d) Sendzimir 12-high.

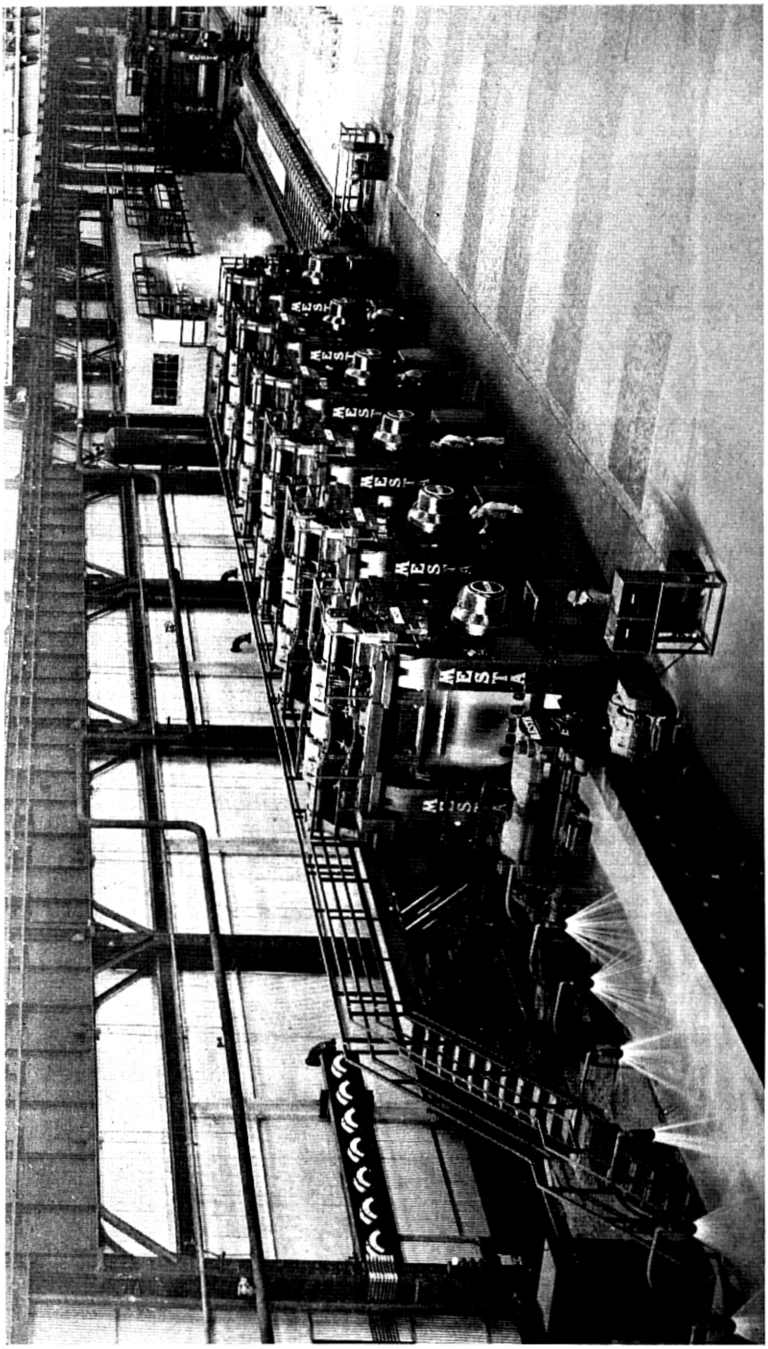


Fig. 15—Continuous strip mill designed for large output, having 6 individual mills in tandem. Courtesy of C. W. Stoker of Carnegie Illinois Steel Corp.

Heat-Treatment

High permeability materials are annealed primarily to relieve the internal strains introduced during fabrication. On the contrary permanent magnet materials are heat-treated to *introduce* strains by precipitating a second phase. Heat-treatments are decidedly characteristic of the materials and their intended uses and are best discussed in detail in connection with them.

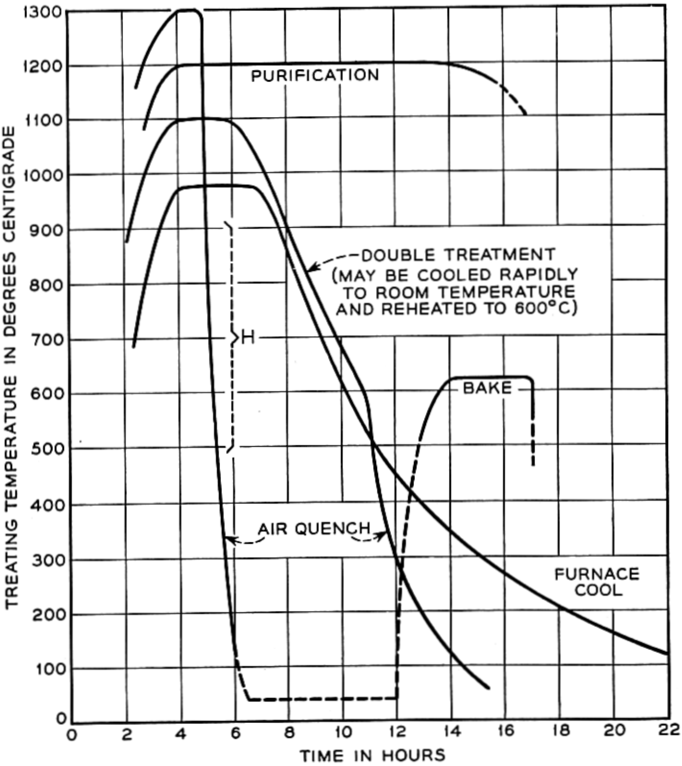


Fig. 16—Some common heat treatments for magnetic materials.

Figure 16 shows some of the commonest treatments in the form of temperature-time curves. The purpose of these various heating and cooling cycles, and typical materials subjected to them, may be listed as follows:

(1) Relief of internal strains due to fabrication or phase-changes (furnace cool). Magnetic iron.

(2) Increase of internal strains by precipitation hardening (air quench and bake). Alnico type of permanent magnets.

(3) Purification by contact with hydrogen or other gases. Silicon-iron (cold rolled), hydrogen-treated iron, Supermalloy.

There are also special treatments, such as those used for "double-treated" permalloy, "magnetically annealed" permalloy, and perminvar.

Occasionally it is necessary to homogenize a material by maintaining the temperature just below the freezing point for many hours. Heat-treatments also may affect grain size and crystal orientation.

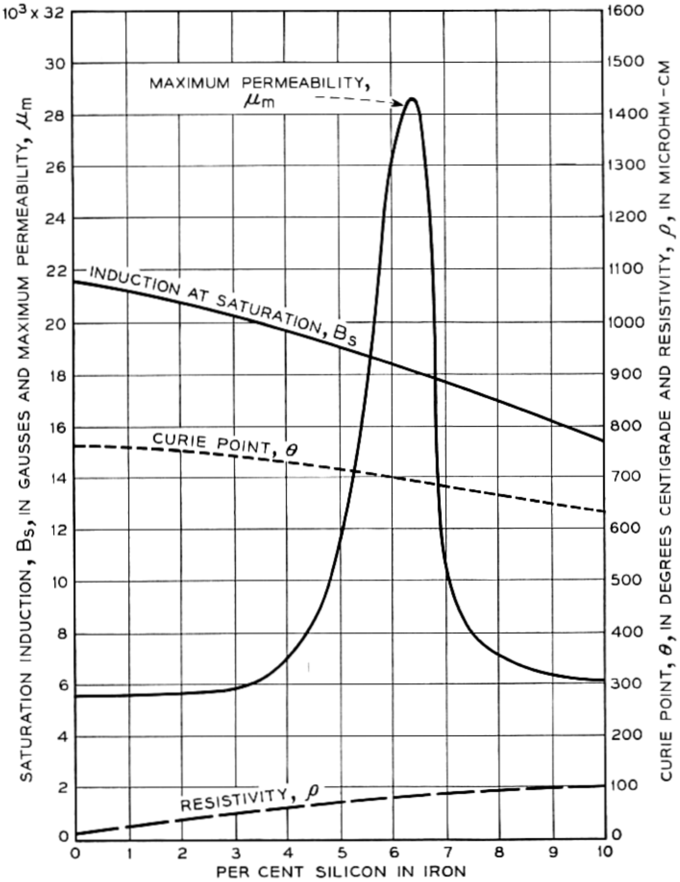


Fig. 17—Variation of some properties of iron-silicon alloys with composition: B_s, saturation intrinsic induction; θ, magnetic transformation point; ρ, electrical resistivity; μ_m, maximum permeability as determined by Miss M. Goertz.

Furnaces for heat-treating have various designs that will not be considered here. A modern improvement has been the use of globar (silicon carbide) heating elements that permit treatment at 1300 to 1350°C in an atmosphere of hydrogen or air.

Further discussion of "Metallurgy and Magnetism" is given in an excellent small book of this title by Stanley.[9]

Effect of Composition

Gross Chemical Composition

The effect of composition on magnetic properties will now be considered, using as examples the more important binary alloys of iron with silicon, nickel or cobalt, on which are based the most useful and interesting materials. The iron-silicon alloys are used commercially without additions, the iron-nickel and iron-cobalt alloys are most useful in the ternary form; and many special alloys, for example material for permanent magnets, contain four or five components.

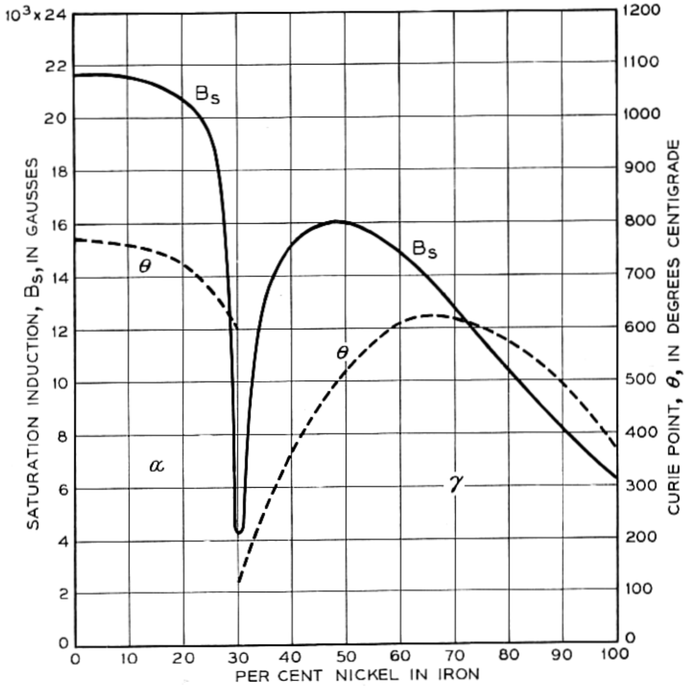


Fig. 18—Variation of B_s and θ with the composition of iron-nickel alloys.

Figure 17 shows four important properties of the iron-silicon alloys of low silicon content, after they have been hot rolled and annealed. The commercial alloys (3 to 5% silicon) are the most useful because they have the best

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[9] J. K. Stanley, Metallurgy and Magnetism, Am. Soc. Metals, Cleveland (1949).

combination of properties of various kinds. The properties shown in the figure are important in determining the best balance: the maximum permeability, μ_m, only indirectly (it is a good measure of hysteresis loss and maximum field necessary in use), and the Curie point, θ, only in a minor role. The saturation B_s, permeability, and resistivity ρ, should all be as high as possible. B_s, θ and ρ are structure insensitive, and vary with composition in a characteristically smooth way, practically independent of heat treatment; μ_m depends on heat treatment (strain), impurities and crystal orientation. There are no phase changes to give sudden changes with composition of properties measured at room temperatures.

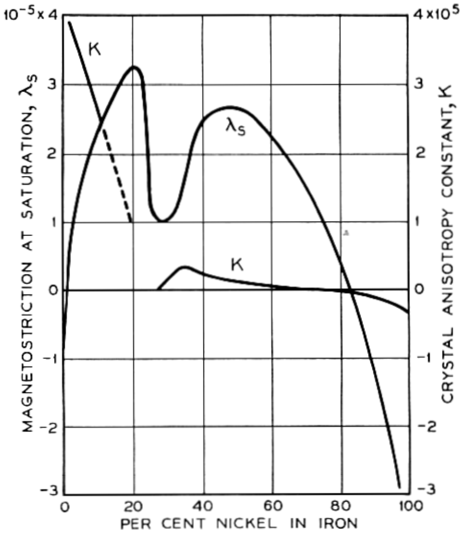

Fig. 19—Variation of saturation magnetostriction, λ_s, and crystal anisotropy, K, with the composition of iron-nickel alloys.

Some of the properties of the iron-nickel alloys are given in Figs. 18 and 19. The change in phase from α to γ at about 30 per cent nickel is responsible for the breaks at this composition. The permeabilities, μ_0 and μ_m, (Fig. 20) show characteristically the effect of heat treatment. The maxima are closely related to the points at which the saturation magnetostriction, λ_s, and crystal anisotropy, K, pass through zero (Fig. 19).

Additions of molybdenum, chromium, copper and other elements are made to enhance the desirable properties of the iron-nickel alloys.

The iron-cobalt alloys, some properties of which are shown in Fig. 21, are usually used when high inductions are advantageous. The unusual course of the saturation induction curve, with a maximum greater than that for any other material, is of obvious theoretical and practical importance. The sud-

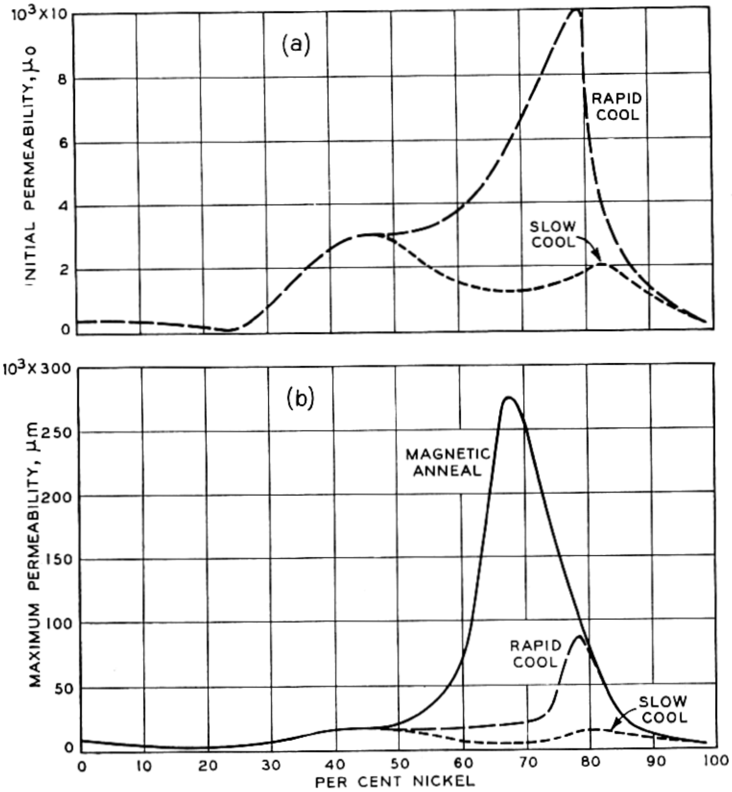

Fig. 20—Dependence of the initial and maximum permeabilities (μ_0, μ_m) of iron-nickel alloys on the heat treatment.

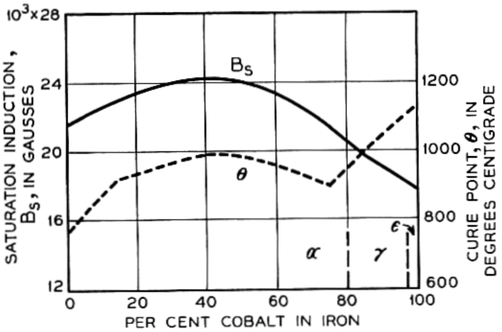

Fig. 21—Variation of B_s and θ of iron-cobalt alloys with composition.

den changes in the Curie point curve are associated with α, γ phase boundaries, as mentioned earlier in this chapter. The peak of the permeability curve (Fig. 22) occurs at the composition for which atomic ordering is stable at the highest temperature (see also Fig. 2). The sharp decline near 95 per cent cobalt coincides with the phase change γ,ϵ at this composition. Additions of vanadium, chromium and other elements are used in making commercial ternary alloys.

Some useful alloys based on the binary iron-silicon, iron-nickel and iron-cobalt alloys are described in Table III.

The *hardening* of material resulting from the precipitation of one phase in another is often used to advantage when magnetic hardness (as in permanent magnets), or mechanical hardness, is desired. To illustrate this process consider the binary iron molybdenum alloys, a partial phase diagram of which is given in Fig. 23. The effect of the boundary between the α and $\alpha + \epsilon$ fields is shown by the variation of the properties with composition (Fig. 24a). Saturation magnetization and Curie point are affected but little, the principle change in the former being a slight change in the slope of the curve at the composition at which the phase boundary crosses 500°C, the temperature below which diffusion is very slow. The Curie point curve has an almost imperceptible break at the composition at which the phase boundary lies at the Curie temperature. The changes of maximum permeability and coercive force are more drastic; μ_m drops rapidly as the amount of the second phase, ϵ, increases and produces more and more internal strain (Fig. 24b), and H_c increases at the same time. The experimental points correspond to a moderate rate of cooling of the alloy after annealing.

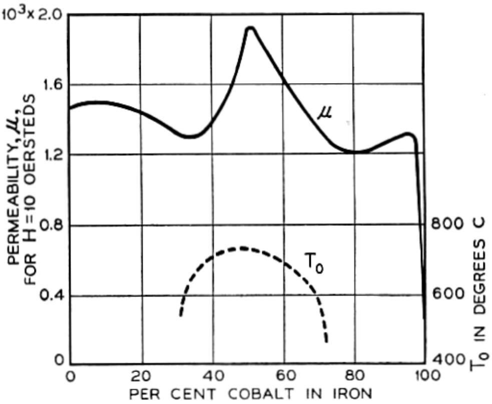

Fig. 22—Variation of permeability at $H = 10$ oersteds, and of the critical temperature of ordering, with the composition of iron-cobalt alloys.

TABLE III

Some Properties of Some Useful Alloys Based on the Fe-Si, Fe-Co and Fe-Ni Binary Systems

Name	Composition (Per cent)	Heat Treatment	Initial Permeability, μ_0	Maximum Permeability, μ_m	Coercive Force, H_c (oersteds)	Saturation Induction, B_s (gausses)	Curie Point, θ (°C)
Hot rolled Silicon Iron....	4Si, 96Fe	800°C	500*	7000	0.5	19700	690
Grain Oriented Silicon Iron..................	3Si, 97Fe	1200°C	1500*	40000	0.15	20000	700
Sendust.................	9Si, 85Fe, 5Al	Cast	30000	120000	0.05	10000	500
45 Permalloy**..........	45Ni, 55Fe	1200°C, H_2	3500	50000	0.07	16000	440
4-79 Permalloy..........	79Ni, 17Fe, 4Mo	1100°C	20000	100000	0.05	8700	420
Mumetal...............	75Ni, 18Fe, 2Cr, 5Cu	1175°C, H_2	20000	100000	0.05	6500	430
Supermalloy.............	79Ni, 16Fe, 5Mo	1300°C, H_2	100000	1000000	0.002	8000	400
Permendur..............	50Co, 50Fe	800°C	800	5000	2.0	24500	980
2V-Permendur...........	49Co, 49Fe, 2V	800°C	800	4500	2.0	24000	980
Hiperco.................	34Co, 64Fe, 1Cr	850°C	650	10000	1.0	24200	—

* Measured at $B = 20$ instead of $B = 0$.

** Similar alloys: Hipenik, Nicaloi, 4750 alloy, and others.

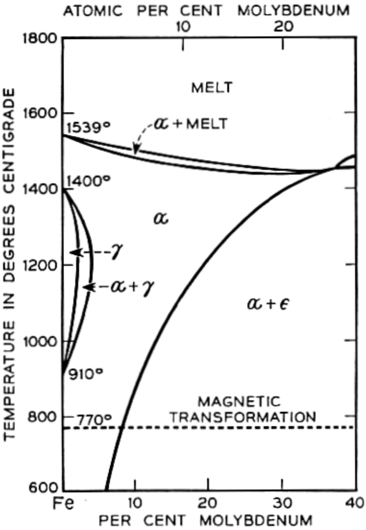

Fig. 23—Phase diagram of iron-rich iron-molybdenum alloys, showing solid solubility curve important in the precipitation-hardening process.

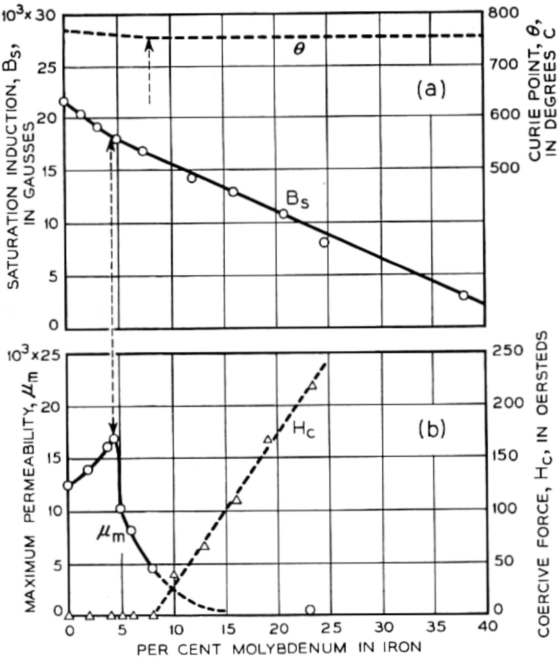

Fig. 24—Change of structure-insensitive properties (θ and B_s) and structure-sensitive properties (μ_m and H_c) with the composition when precipitation-hardening occurs.

When the amount of the second phase is considerable (as in the 15% Mo alloy) it is common practice to quench the alloy from a temperature at which it is a single phase (e.g. 1100 or 1200°C) and so maintain it temporarily as such, and then to heat it to a temperature (e.g., 600°C) at which diffusion proceeds at a more practical rate. During the latter step the second phase separates slowly enough so that it can easily be stopped at the optimum point, after a sufficient amount has been precipitated but before diffusion has been permitted to relieve the strains caused by the precipitation. A conventional heat treatment for precipitation-hardening of this kind, used on many permanent magnet materials, has already been given in Fig. 16.

In some respects the development of atomic order in a structure is like the precipitation of a second phase. When small portions of the material become ordered and neighboring regions are still disordered, severe local strains may be set up in the same way that they are during the precipitation hardening described above. The treatment used to establish high strains is the same as in the more conventional precipitation hardening. The decomposition of an ordered structure in the iron-nickel-aluminum system has been held responsible, by Bradley and Taylor,[10] for the good permanent magnet qualities of these alloys.

Some of the common permanent magnets, heat treated to develop internal strains by precipitation of a second phase, or by the development of atomic ordering, are described in Table IV.

The changes in properties to be expected when the composition varies across a phase boundary of a binary system are shown schematically by the curves of Fig. 25.

Impurities

The principle of precipitation hardening, as just described, applies also to the lowering of permeability by the presence of accidental impurities. For example, the solubilities of carbon, oxygen and nitrogen in iron, described by the curves of Fig. 26, are quite similar in form to the curve separating the α and $\alpha + \epsilon$ areas of the iron-molybdenum system of Fig. 23; the chief difference is that the scale of composition now corresponds to concentrations usually described as impurities. One expects, then, that the presence of more than 0.04 per cent of carbon in iron will cause the permeability of an annealed specimen to be considerably below that of pure iron. The amount of carbon present in solid solution will also affect the magnetic properties.

Because the amounts of material involved are small, it is difficult to carry out well defined experiments on the effects of each impurity, especially in

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[10] A. J. Bradley and A. Taylor, *Proc. Roy. Soc.* (London) 166, 353–75 (1938).

TABLE IV

Some Useful Permanent Magnets and Their Properties

Name	Composition (Per cent)*	Fabrication	Heat Treatment	H_c	B_r	Mechanical Properties
Carbon Steel	1Mn, 0.9C	HR, PM	Q800	50	10000	H, S
Tungsten Steel	5W, 0.3Mn, 0.7C	HR, PM	Q850	70	10300	H, S
Chromium Steel	3.5Cr, 0.3Mn, 0.9C	HR, PM	Q830	65	9700	H, S
Cobalt Steel	36Co, 4Cr, 5W, 0.7C	HR, PM	Q950	240	9500	H, S
Remalloy (Comol)	17Mo, 12Co	HR, PM	Q1200, B700	250	10500	H
Alnico 2	12Co, 17Ni, 10Al, 6Cu	C, G	A1200, B600	550	7200	H, B
Alnico 5	24Co, 14Ni, 8Al, 3Cu	C, G	A1300, **B600	550	12500	H, B
Alnico 12	35Co, 18Ni, 6Al, 8Ti	C, G	Cast, B650	950	5800	H, B
Alcomax	25Co, 11Ni, 8Al, 6Cu	C, G	A1300, **B600	550	12500	H, B
Vicalloy	52Co, 10V	C, Cr, PM	B600	300	8800	D
Cunife	20Ni, 60Cu	C, Cr, PM	B600	550	5400	D
Platinum-Cobalt	77Pt, 23Co	C, Cr, PM	Q1200, B650	2600	4500	D
Silmanal	87Ag, 9Mn, 4Al	C, Cr, PM		6000†	550	D

* Remainder iron
Q—quenched from indicated centigrade temperature in oil
A—cooled in air from indicated temperature
B—baked at indicated temperature
HR—hot rolled
CR—cold rolled
PM—punched or machined
C—cast
G—ground
** Cooled in magnetic field
† Coercive force for I = 0
H—hard
B—brittle
D—ductile or malleable
S—strong

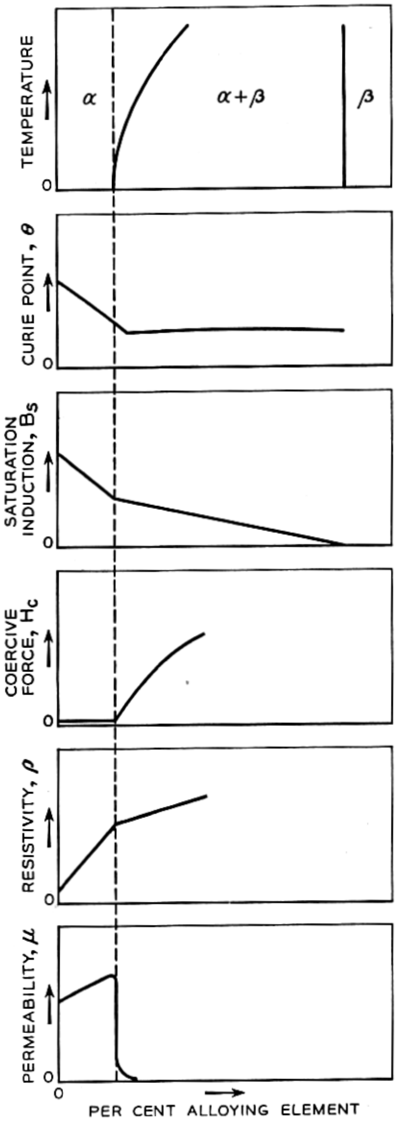

Fig. 25—Diagrams illustrating the changes in various properties that occur when a second phase precipitates.

the absence of disturbing amounts of other impurities. Two examples of the effect of impurities will be given, in addition to Fig. 8. In Fig. 27 Yensen and Ziegler[11] have plotted the hysteresis loss as dependent on carbon content,

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[11] T. D. Yensen and N. A. Ziegler, *Trans. Am. Soc. Metals* 24, 337–58 (1936).

the curve giving the mean values of many determinations. The hysteresis decreases rapidly at small carbon contents, when these are of the order of magnitude of the solid solubility at room temperature.

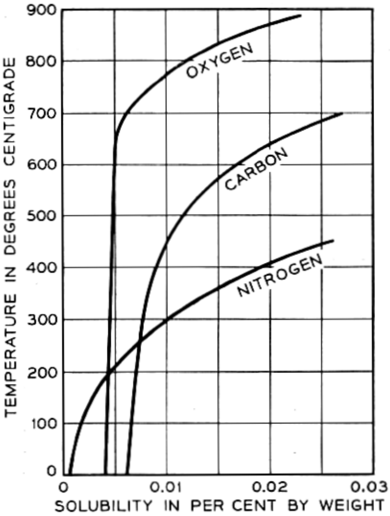

Fig. 26—Approximate solubility curves of carbon, oxygen and nitrogen in iron.

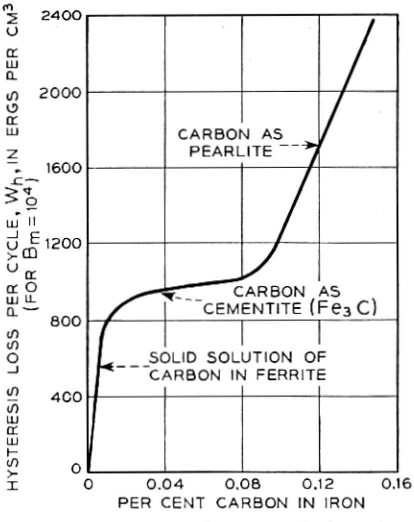

Fig. 27—Effect of carbon content on hysteresis in iron. *Yensen and Ziegler.*

Cioffi[12] has purified iron from carbon, oxygen, nitrogen and sulfur by heating in pure hydrogen at 1475°C, and has measured the permeability

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[12] P. P. Cioffi, *Phys. Rev. 39*, 363–7 (1932).

at different stages of purification. Table V shows that impurities of a few thousandths of a per cent are quite effective in depressing the maximum permeability of iron.

Carbon and nitrogen, present as impurities, are known to cause "aging" in iron—that is, the permeability and coercive force of iron containing these elements as impurities will change gradually with time when maintained somewhat above room temperature. As an example, a specimen of iron was maintained for 100 hours first at 100°C, then 150°C, then 100°C, and so on.

TABLE V

Maximum permeability of Armco iron with different degrees of purification, effected by heat treatment in pure hydrogen at 1475°C for the times indicated (P. P. Cioffi).
Analyses from R. F. Mehl (private communication to P. P. Cioffi).

Time of Treatment in Hours	μ_m	Composition in Per Cent					
		C	S	O	N	Mn	P
0	7000	0.012	0.018	0.030	0.0018	0.030	0.004
1	16000	.005	.010	.003	.0004	—	—
3	30000	.005	.006	.003	.0003	—	—
7	70000	.003	—	.003	.0001	—	—
18	227000	.005	$<.003$	.003	.0001	.028	.004
Precision of analysis.........		.001	.002	.002	.0001		

The corresponding changes in coercive force are given in the diagram of Fig. 28. A change of about 2-fold is observed.

SOME IMPORTANT PHYSICAL PROPERTIES

There are many physical characteristics that are important in the study of ferromagnetism from both the practical and the theoretical point of view. These include the resistivity, density, atomic diameter, specific heat, expansion, hardness, elastic limit, plasticity, toughness, mechanical damping, specimen dimensions, and numerous others. In a different category may be mentioned corrosion, homogeneity and porosity. Most of these properties are best discussed in connection with specific materials or properties; only the most important characteristics will be mentioned here. A table of the atomic weights and numbers, densities, melting points, resistivities and coefficients of thermal expansion of the metallic elements, is readily available in the Metals Handbook.

Dissolving a small amount of one element in another increases the *resistivity* of the latter. To show the relative effects of various elements, the common binary alloys of iron and of nickel are shown in Figs. 29 and 30. From a theoretical standpoint it is desirable to understand (1) the relatively high resistivity of the ferromagnetic elements compared to their neighbors in the periodic table and (2) the relative amounts by which the resistivity of iron (or cobalt or nickel) is raised by a given atomic percentage of various other elements. From a practical standpoint, a high resistivity is usually desirable in order to decrease the eddy-current losses in the material, and so decrease the power wasted and the lag in time between the cause and effect, for example, the time lag of operation of a relay.

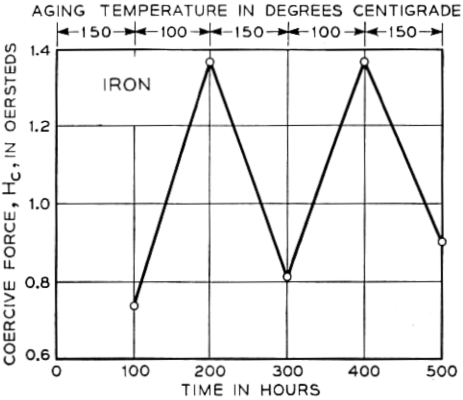


Fig. 28—Effect of nitrogen impurity on the coercive force of iron annealed successively at 100 and 150°C.

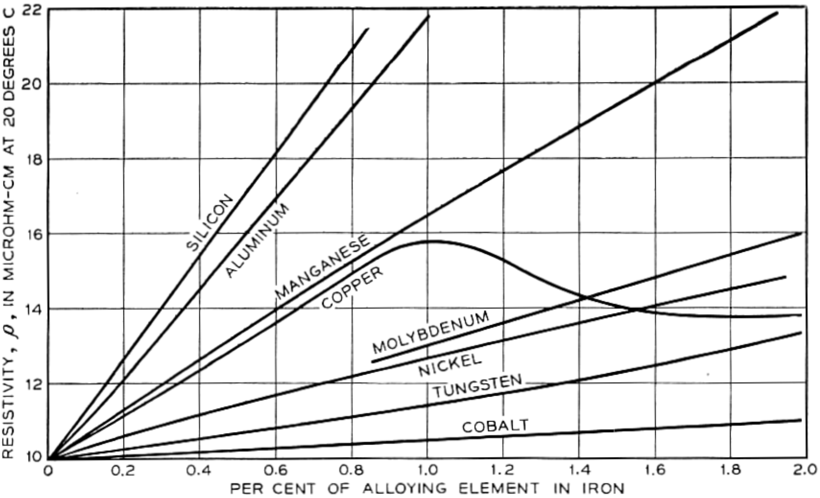


Fig. 29—Dependence of resistivity on the addition of small amounts of various elements to iron.

Knowledge of the *atomic diameter* is important in considering the effects

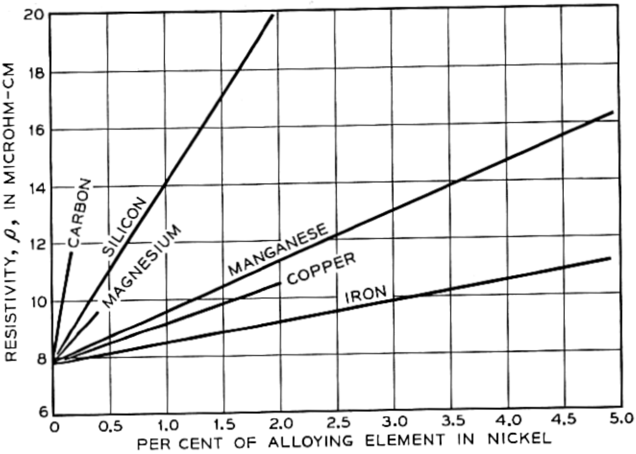


Fig. 30—Resistivity of various alloys of nickel.

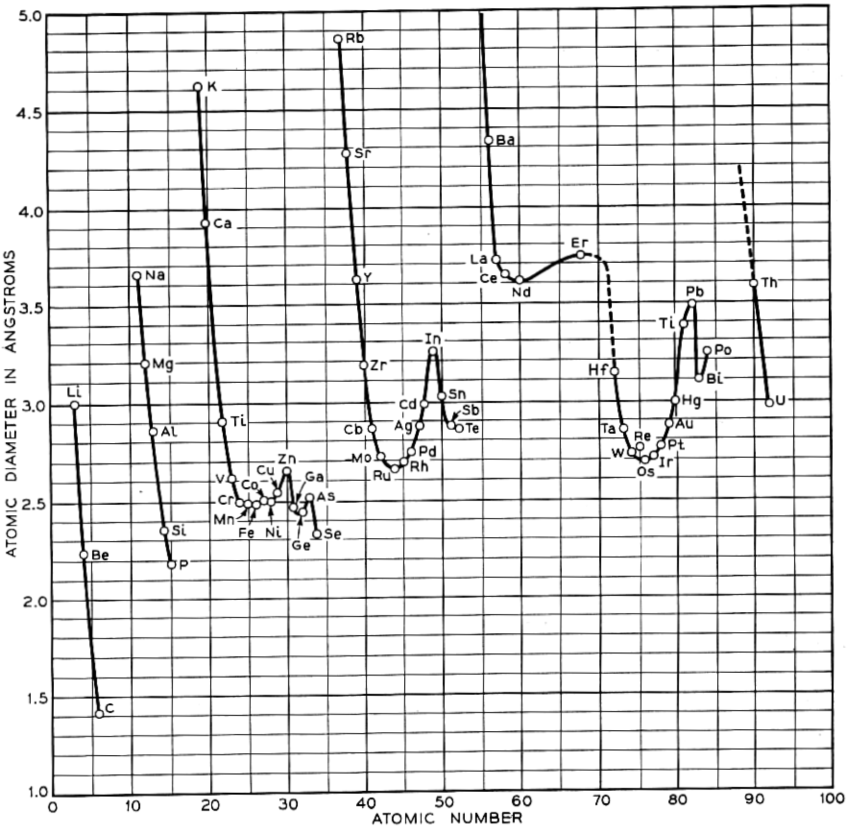
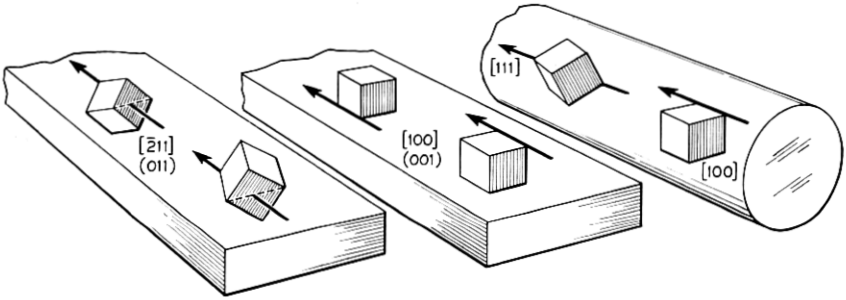


Fig. 31—Atomic diameter of various metallic elements.

of alloying elements, and values for the metallic and borderline elements are shown in Fig. 31. Most of the values are simply the distances of nearest approach of atoms in the element as it exists in the structure stable at room temperature. Atomic diameter is especially important in theory because the very existence of ferromagnetism is dependent in a critical way on the distance between adjacent atoms. This has been discussed more fully in a previous paper.[13]

Even when no phase change occurs in a metal, important *changes in structure* occur during fabrication and heat treatment, and these are complicated and imperfectly understood. When a single crystal is elongated by tension, slip occurs on a limited number of crystal planes that in general are inclined to the axis of tension. As elongation proceeds, the planes on which slip is taking place tend to turn so that they are less inclined to the axis. In this way a definite crystallographic direction approaches parallelism with the length of the specimen. In a similar but more complicated way, any of the usual methods of fabrication cause the many crystals of which it is composed to assume a non-random distribution of orientations, often referred to as preferred or *special orientations*, or *textures*. Some of the textures reported for cold rolled and cold drawn magnetic materials are given in Table VI, taken from the compilation by Barrett.[14] The orientations of the cubes which are the crystallographic units are shown in Fig. 32 (a) and (c) for cold rolled sheets and cold drawn wires of nickel.



(a) ROLLED **(b) RECRYSTALLIZED** **(c) DRAWN**

Fig. 32—The preferred orientations of crystals in nickel sheet and wire after fabrication and after recrystallization.

Since the magnetic properties of single crystals depend on crystallographic direction (anisotropy), the properties of polycrystalline materials in which there is special orientation will also be direction-dependent. In fact it is difficult to achieve isotropy in any fabricated material, even if fabrication involves no more than solidifying from the melt. The relief of the internal

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[13] R. M. Bozorth, *Bell Sys. Tech. Jl.* 19, 1–39 (1940).

[14] C. S. Barrett, Structure of Metals, McGraw Hill, New York (1943).

strains in a fabricated metal by annealing proceeds only slowly at low temperatures (up to 600°C for most ferrous metals) without noticeable grain growth or change in grain orientation, and is designated *recovery*. The principle change is a reduction in the amplitude of internal strains, and this can be followed quantitatively by X-ray measurements. Near the point of complete relief distinct changes occur in both grain size and grain orientation, and the material is said *to recrystallize*. At higher temperatures grain growth increases more rapidly. The specific temperatures necessary for both recovery and recrystallization depend on the amount of previous deformation, as shown in Fig. 33. Special orientations are also present in fabricated materials after recrystallization, and some of these are listed in Table VI and illustrated for nickel in Fig. 32 (b).

As an example of the dependence of various magnetic properties on direction, Fig. 34 gives data of Dahl and Pawlek[15] for a 40 per cent nickel iron alloy reduced 98.5 per cent in area by cold rolling and then annealed at 1100°C. After further cold rolling (50 per cent reduction) the properties are as described in Fig. 35.

TABLE VI

Preferred Orientations in Drawn Wires and Rolled Sheets, Before and After Recrystallization, and in Castings (Barrett[14])

The rolling plane and rolling direction, or wire axis, or direction of growth, are designated

Metal	Crystal Structure	Drawn wires		Rolled Sheets		As Cast
		As Drawn	Recrystallized	As Rolled	Recrystallized	
Iron.......	BCC	[110]	[110]	(001), [110] and others	(001), 15° to [110]	[100]
Cobalt.....	HCP	—	—	(001)	—	—
Nickel.....	FCC	[111] and [100]	—	(110), [112] and others	(100), [001]	

The mechanical properties ordinarily desirable in practical materials are those which facilitate fabrication. Mild steel is often considered as the nearest approach to an ideal material in this respect. Silicon iron is limited by its brittleness, which becomes of major importance at about 5 per cent silicon; this is shown by the curve of Fig. 36. Permalloy is "tougher" than iron or mild steel and requires more power in rolling and more frequent annealing between passes when cold-rolled, but can be cold-worked to smaller dimensions. If materials have insufficient stiffness or hardness, parts of apparatus made from them must be handled with care to avoid bending and consequent lowering of the permeability. If the hardness is too great the material must be ground to size. This is the case with some permanent magnets.

[15] O. Dahl and F. Pawlek, *Zeits. f. Metallkunde* 28, 230–3 (1936).

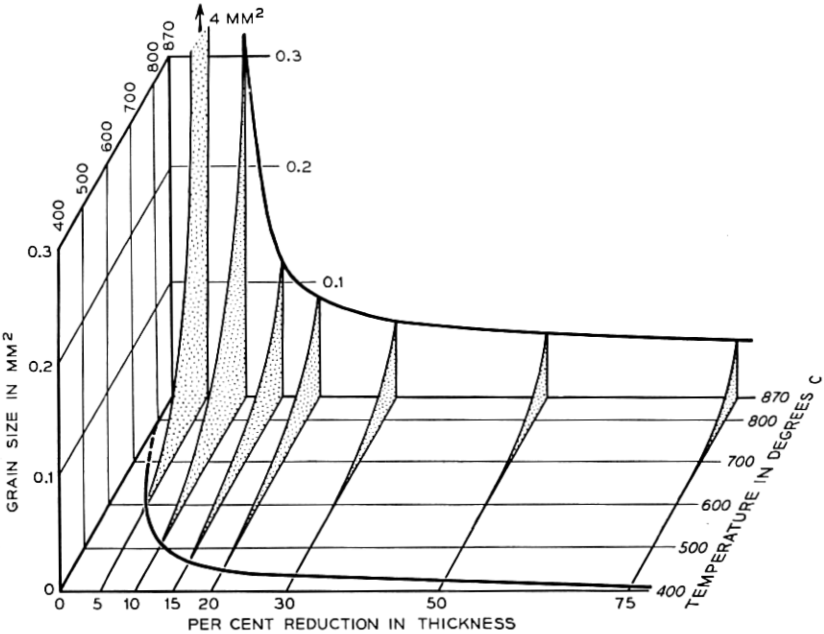

Fig. 33—Dependence of the grain size of iron on the amount of deformation and on the temperature of anneal. *Kenyon.*

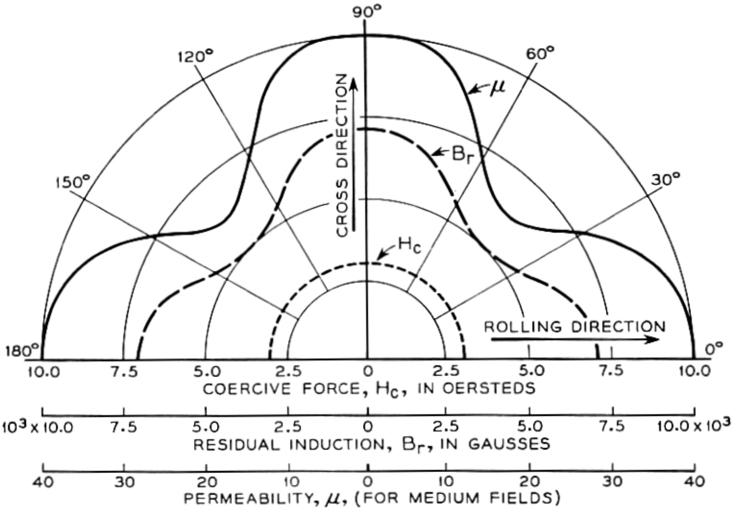

Fig. 34—Variation of magnetic properties with the direction of measurement in a sheet of iron-nickel alloy (40% Ni) severely rolled (98.5%) and annealed at 1100°C.

The effect of size of a magnetic specimen is often of importance. This is well known in the study of *thin films*, and *fine powders* in which the smallest dimension is about 10^{-4} cm or less. Many studies have been made of thin electrodeposited and evaporated films. Generally it is found that the permeability is low and the coercive force high. The interpretation is uncertain because it is difficult to separate the effects of strains and air gaps from the intrinsic effect of thickness, though it is known that each one of these variables has a definite effect. As one example of the many experiments, we

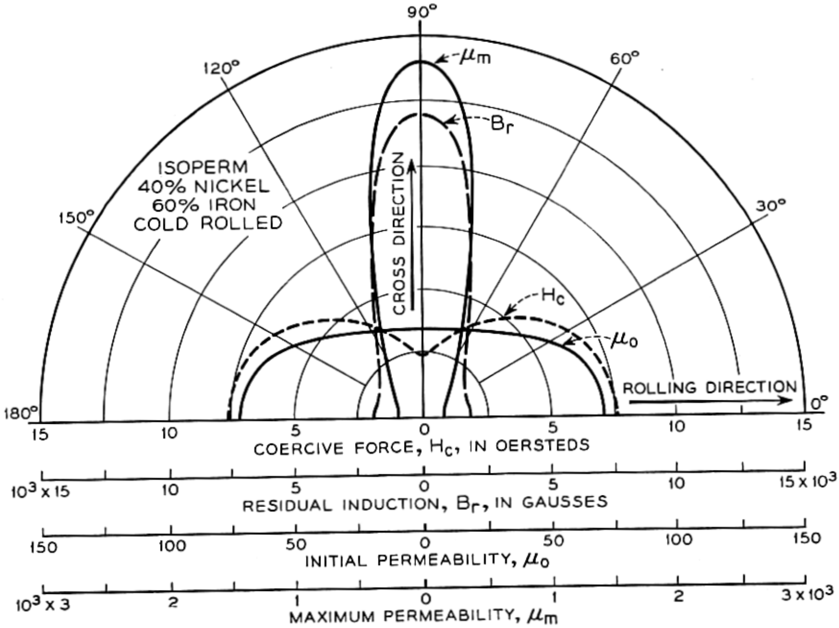

Fig. 35—Properties of the same material as that of Fig. 34, after it has been rolled, annealed, and again rolled.

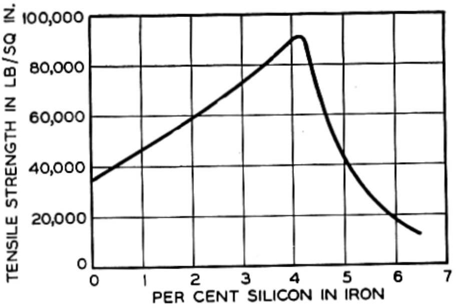

Fig. 36—Variation of the breaking strength of iron-silicon alloys, showing the onset of brittleness near 4 per cent silicon.

will show here the effect of the thickness of electrodeposited films of cobalt. Magnetization curves are shown in Fig. 37 according to previously unpublished work of the author.

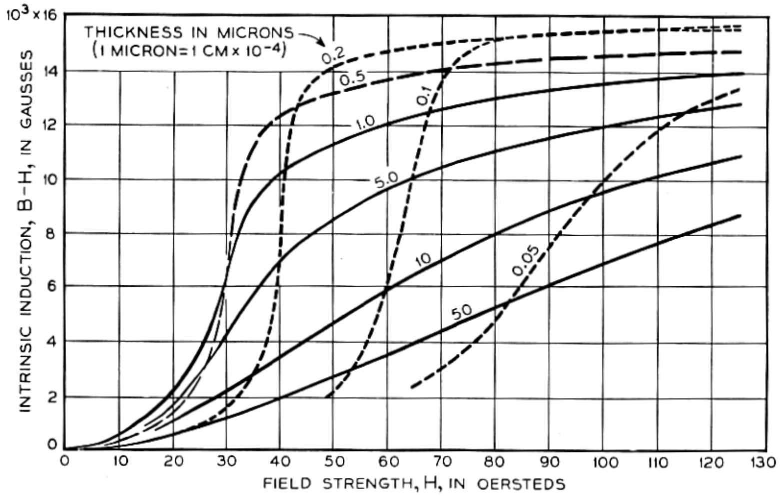

Fig. 37—Dependence of the magnetization curves of pure electrodeposited cobalt films on the thickness.

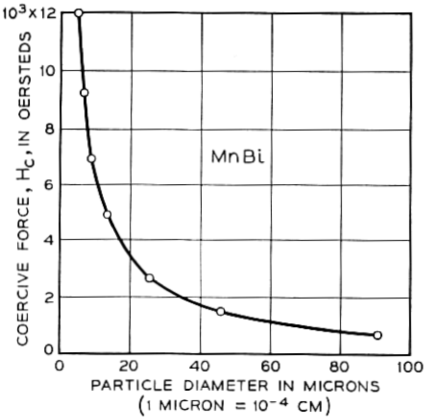

Fig. 38—Dependence of coercive force on the particle size of MnBi powder. *Guillaud.*

The high coercive force obtained in fine powders by Guillaud[16] is one of the most clear cut examples of the intrinsic effect of particle size. The coercive force increases by a factor of 15 as the size decreases to 5×10^{-4} cm (Fig. 38).

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[16] C. Guillaud, Thesis, Strasbourg (1943).

Properties Affected by Magnetization

In addition to the magnetization, other properties are changed by the direct application of a magnetic field. Some of these, and the amounts by which they may be changed, are as follows:

Length and volume (magnetostriction) (0.01%)
Electrical resistivity (5%)
Temperature (magnetocaloric effect; heat of hysteresis) (1°C)
Elastic constants (20 per cent)
Rotation of plane of polarization of light (Kerr and Faraday effects) (one degree of arc)

In addition to these properties there are others that change with temperature because the magnetization itself changes. Thus there is "anomalous" temperature-dependence of:

Specific heat
Thermal expansion
Electrical resistivity
Elastic constants
Thermoelectric force

and of other properties below the Curie point of a ferromagnetic material, even when no magnetic field is applied.

Also associated with ferromagnetism are galvanomagnetic, chemical and other effects.