

Theory of the Heat Treatment of Magnetic Materials

The magnetic permeabilities of certain alloys have been increased enormously by heat treating them in a magnetic field.¹ A permeability of over 600,000 has been attained in permalloy containing about 65 percent nickel. The purpose of this note is to discuss the nature of the changes that occur in these materials during the heat treatment in the field and more generally to discuss those structural changes, peculiar to ferromagnetic materials, which occur during heat treatment.

As a ferromagnetic specimen cools through the Curie point in the absence of an applied field, modern magnetic theory postulates² that small regions or domains become magnetized to saturation in a definite crystallographic direction, one of the $\langle 100 \rangle$ directions (cube edges) in the case of 65 permalloy.³ As this magnetization develops, magnetostrictive stresses arise which tend to change the shapes of the domains, in the case of this alloy to increase the dimension in the direction of the local magnetization and decrease those at right angles. This process is illustrated in Fig. 1, where (a) represents a part of the material, above the Curie point, which is to become part of a single domain when cooled. A spherical form is assumed merely for convenience. As the specimen cools through the Curie point and becomes ferromagnetic, the domain becomes saturated in some direction as shown in (b) and also tends to change its shape because of its magnetostriction, as indicated in an exaggerated way by the dotted ellipse. If the domain were free in space it would assume the latter shape immediately, but actually it is surrounded by other domains which constrain it, preventing its change in shape. However, if the specimen is held for sufficient time at a high enough temperature (below the Curie point), the sphere will actually assume the shape shown in (c) by plastic flow of the surrounding domains. It is the latter idea, of plastic flow on account of the magnetostriction in the domains, that is fundamental to the theory of heat treatment here presented. The direction of magnetization in each domain is parallel to a crystallographic axis $\langle 100 \rangle$,

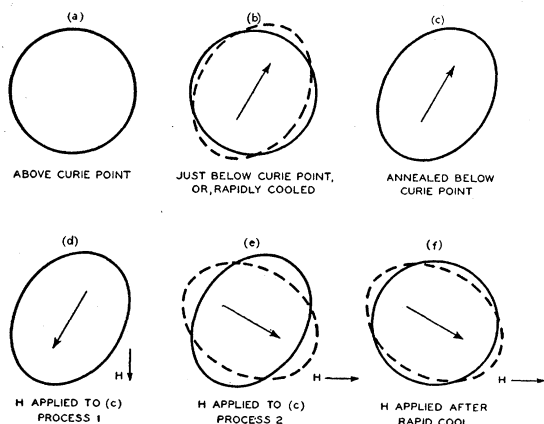


FIG. 1. The shapes of domains as influenced by heat treatment.

but the various domains will be oriented in equal numbers in all directions. When a field is applied for measurement at room temperature, the magnetization of the specimen as a whole will be changed in three ways: (1) reversal of the magnetization (180° change) in some of the domains; (2) change in the direction of magnetization in other domains by 90° , to a different $\langle 100 \rangle$ direction; and (3) rotation of the magnetization vector out of a $\langle 100 \rangle$ direction. The last process occurs to a considerable extent only in relatively high fields, and does not concern us here. Process (1), represented in Fig. 1 as a change from (c) to (d), takes place with a minimum of energy loss, because magnetostrictive strain is independent of the sign of the magnetization and the shape of the domain is the same before and after the change. Process (2), (c) to (e), requires work to be done against elastic forces. This additional energy involved in Process (2) as compared with Process (1) seems to be the reason for the more frequent occurrence of the latter process, as determined by Heaps⁴ and more directly by McKeehan and Clash.⁵

Obviously, the greater the proportion of changes of kind (1) the less the energy loss attending magnetization to technical saturation, and the greater the maximum permeability. An increase in the proportion of changes of kind (1) relative to kind (2) is just the result one attains when the material is heat treated in a magnetic field, for then the domains are *all* magnetized in the $\langle 100 \rangle$ direction nearest to that of the field and are stabilized in those positions by plastic flow. When the material is demagnetized at room temperature, half of the domains reverse (Process 1), and when the specimen is magnetized in the same or opposite direction to that in which the field acted during heat treatment, reversals again occur with a minimum of energy loss. On the other hand, if the field applied for measurement is perpendicular to that applied during heat treatment, one expects relatively large strains to be set up in the material (Fig. 1 (e)) and consequently much lower permeability. The experimental results are in accord with these views: the ratio of permeabilities in the two directions has been found to be as large as 200 to 1.

If the material is *cooled rapidly* enough from some temperature above the Curie point to a temperature below the recrystallization temperature, there will not be time for the domain to change its shape as shown in Fig. 1 (a) to (c), and the magnetostrictive stress will persist at room temperature as indicated by (b). When a field is then applied and the direction of magnetization changes by 90° , Fig. 1 (f), the elastic strains set up will have a different direction from that which they had before the field was applied, but will be of the same magnitude. Consequently, the energy loss will be less than that attending the change from (c) to (e) for the slowly cooled material. As a result,

¹ R. M. Bozorth, J. F. Dillinger and G. A. Kelsall, *Phys. Rev.* **45**, 742 (1934).

² See various papers by W. L. Webster, W. Heisenberg, R. Becker, F. Bitter, R. M. Bozorth.

³ F. Lichtenberger, *Ann. d. Physik* **15**, 45 (1932).

⁴ C. W. Heaps, *Phys. Rev.* **45**, 320 (1934).

⁵ L. W. McKeehan and R. F. Clash, Jr., *Phys. Rev.* **45**, 839 (1934).

⁶ Curve (a) from G. W. Elmen, *J. Frank. Inst.* **207**, 583 (1929); curve (b), from his unpublished data, is for a cooling rate of 20° to 40°C per second.

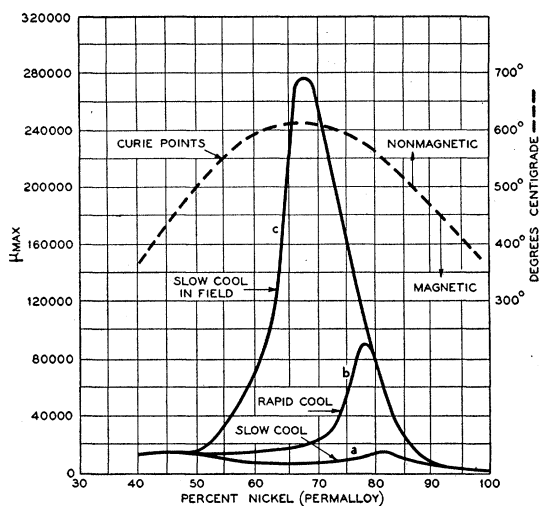


FIG. 2. The maximum permeabilities of Fe-Ni alloys as influenced by heat treatment. The dotted line shows the Curie points.

the maximum permeability will be higher for rapidly cooled material than for that slowly cooled in the absence of applied field; but the highest permeability of all will be attained in the material heat treated in a field. The maximum permeabilities⁶ of the iron-nickel alloys are shown in Fig. 2 as a function of composition, for the three kinds of heat treatment discussed in relation to this theory.

One may consider whether the magnitude of the magnetostrictive strain, $\Delta l/l$, is adequate to change the magnetic properties as much as various heat treatments are observed to change them. Using the saturation value of $\Delta l/l$ for 65 permalloy, 2×10^{-5} , and Young's modulus, 2×10^4 kg/mm², we find that a tension of about 0.4 kg/mm² will produce the same strain as magnetization to saturation. Measurement shows that the application of this stress to a specimen slowly cooled without applied field, increases the maximum permeability from 7000 to 25,000, the latter value being larger than that characteristic of the rapidly cooled unstrained material. This similarity in the effect of applied tension and magnetostrictive stress gives strong support to the fundamental idea of the theory.

According to the theory described, it is not to be expected that different magnetic behavior will result from different heat treatments of annealed material if the Curie point or a phase transformation point lies between room temperature and the temperature at which a slightly strained crystal relieves itself of strain. That this expectation is correct for the iron-nickel alloys is shown plainly in Fig. 2 where the Curie points,⁷ shown by the dotted curve, lie above the strain-relief temperature for these alloys (400 to 500°C) for compositions between 50 and 85 percent nickel. It has been found also that heat treatment in a field has a negligible effect upon nickel, which has a low Curie point, and only a small effect upon iron, which has complicated magnetostriction. This heat treatment has also been

found ineffective in certain iron-cobalt-nickel alloys which have low Curie points or low phase transformation temperatures.

R. M. BOZORTH

Bell Telephone Laboratories,
New York, N. Y.,
July 12, 1934.

⁷ F. Hegg, Arch. d. Sci. Phys. et Nat. 3, 15-45 (1910). The alloys actually used in obtaining curves (a), (b) and (c) of Fig. 2 contain 0.5 to 1.0 percent Mn and other impurities, and their Curie points are somewhat lower (perhaps by 50°C) than those reported by Hegg.

The Nuclear Spin of Columbium

In a preliminary report¹ the value of the quantum number of nuclear spin for columbium⁹³ was given as $I \geq 7/2$. A more detailed study has been made of the hyperfine structure of the columbium spectrum. The discharge in a liquid air-cooled Schüller tube was used as a light source. The instrument of high resolving power used was a Fabry-Perot etalon. A three prism flint glass spectrograph was used as the instrument of auxiliary dispersion. The columbium spectrum has been photographed from $\lambda 4000$ to $\lambda 7000$ with etalon separators ranging in width from 2.5 mm to 15 mm. The results of the investigation may be summarized as follows: Measurements of the intervals between the hyperfine structure components of $\lambda 4059$, 4080 and 4649 indicate definitely a value $I = 9/2$ for columbium. Relative intensity measurements on the hyperfine structure components of $\lambda 4117$ and $\lambda 4649$ also indicate a value $I = 9/2$. The hyperfine structure patterns of the prominent unclassified lines $\lambda 4672$, 4675, 5344 and 6661 can be satisfactorily explained if $9/2$ is accepted as the value of I for columbium. A detailed description of this investigation will be submitted for publication soon.

STANLEY S. BALLARD

University of California,
Berkeley, California,
July 3, 1934.

¹ N. S. Grace and S. S. Ballard, Phys. Rev. 44, 128 (1933).

Fundamental Frequencies of Acetylene

Six frequencies were found in liquid acetylene by Raman scattering by using 4358 Hg and 4046 Hg: 382(5), 618(2), 631(5), 1762(1), 1959(10), 3338(5) cm⁻¹. The last two had been obtained before by Daure¹ and Daure and Kastler.² These new frequencies will be used to interpret the infrared bands of acetylene. This last point will be presented at the forthcoming American Chemical Society meeting in Cleveland.

GEORGE GLOCKLER
CHARLES MORRELL

University of Minnesota,
July 11, 1934.

¹ Daure, Trans. Faraday Soc. 25, 825 (1929).

² Daure and Kastler, Comptes Rendus 192, 1721 (1931).