One can probably assume a packing factor of the order of 50 percent for these clusters, whereupon Weil[9] has shown that the coercive force will be cut in half. In addition, this clustering makes it extremely difficult to line up the particles. If we assume that Néel's[10] calculation for randomly oriented cubic crystallites applies to both hexagonal cobalt and iron with shape anisotropy, then the theoretical value for iron particles of $1\frac{1}{2}$ to 1 shape anisotropy is reduced from 3000 oersteds for widely separated particles to approximately 500, and that for cobalt particles from 6000 oersteds to 1000 oersteds.

[9] L. Weil and S. Marfoure, Compt. rend. **225**, 229 (1947).
[10] L. Néel, Compt. rend. **224**, 1488 (1947).

It is apparent that in spite of having particles of $1\frac{1}{2}$ to 1 shape anisotropy, steps must still be taken (1) to better evaluate the effect of shape and size distribution, (2) to evaluate the effect of clustering on lining up of the particles, and (3) to evaluate the "apparent" packing factor due to clustering.

It is hoped that further work along these lines will lead to an experimental evaluation of the contribution of shape anisotropy to coercive force.

ACKNOWLEDGMENT

I wish to thank T. O. Paine for his many helpful suggestions and E. F. Fullam for his generous contribution to the taking of the electron micrographs.

REVIEWS OF MODERN PHYSICS VOLUME 25, NUMBER 1 JANUARY, 1953

A New Permanent Magnet from Powdered Manganese Bismuthide

EDMOND ADAMS

U. S. Naval Ordnance Laboratory, White Oak, Silver Spring 19, Maryland

BECAUSE the present demand for cobalt and nickel greatly exceeds their availability, there has been an increasing interest, both in this country and abroad, in the development of permanent magnets not containing these elements. The Magnetics Division of the Naval Ordnance Laboratory, as part of its program of developing improved and nonstrategic magnetic materials for military and industrial use, has developed bismanol, a new high energy product permanent magnet. This magnet was prepared by hot-pressing the finely pulverized anisotropic intermetallic compound, manganese bismuthide (MnBi). A typical demagnetization curve for bismanol is illustrated in Fig. 1, which shows a maximum energy product $(BH)_{max}$ of 4.3×10^6 gauss-oersteds, a coercive force (H_c) of 3400 oersteds, and a residual flux density (B_r) of 4300 gauss. That this was possible was first predicted by Guillaud[1] as early as 1939. Guillaud, in

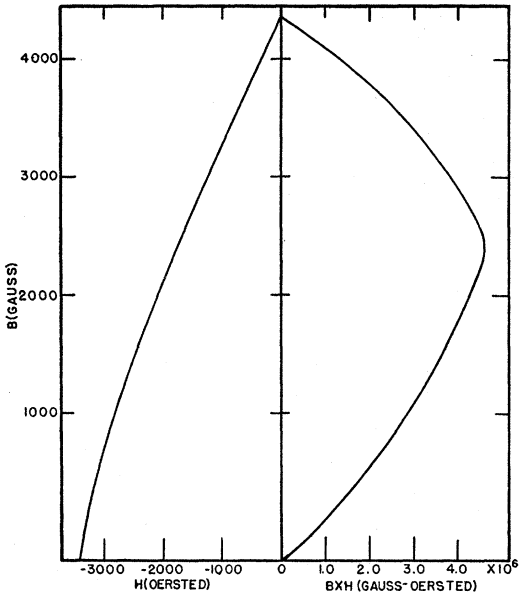

FIG. 1. Demagnetization and energy product curves—bismanol.

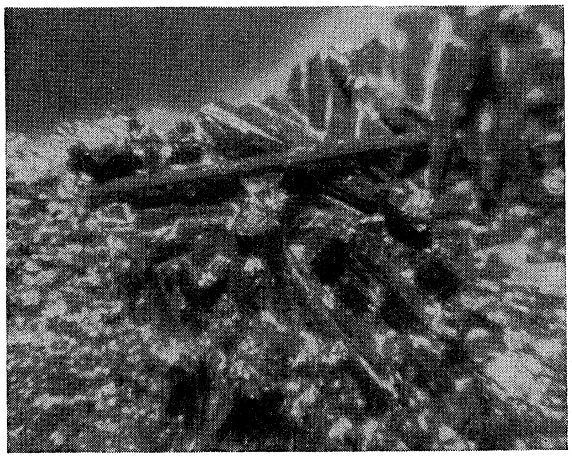

FIG. 2. Hexagonal crystals of MnBi.

[1] C. Guillaud, thesis, University of Strasbourg (Strasbourg, France), 1943.

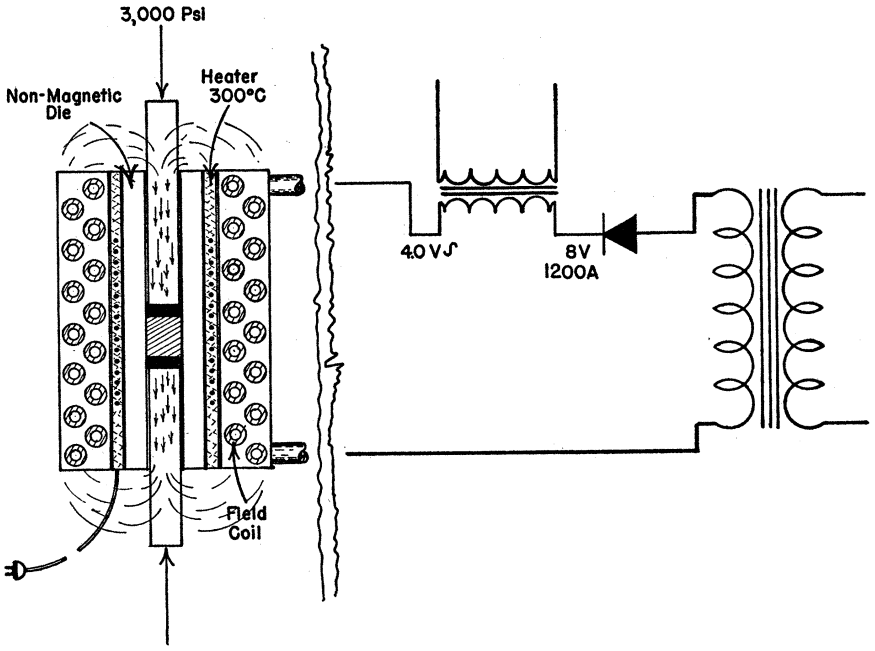

Fig. 3. Hot-pressing oriented MnBi powder into bismanol magnets.

addition to measuring the saturation moment, magnetic crystal anisotropy, and Curie temperature, established the dependence of the high coercive force of manganese bismuthide on its high crystal anisotropy and reduced particle size. Because of these considerations, MnBi was chosen for this investigation in spite of the practical difficulties involved.

Manganese and bismuth powders were heated in a rotating furnace to 700°C for the reaction to take place and aged at 450°C for MnBi crystals to increase in size. At this stage bismuth was allowed to diffuse through a MgO crucible. This exposed some almost perfect hexagonal crystals of MnBi as shown in Fig. 2. They were identified as the compound MnBi by x-ray diffraction as shown in Table I. Normally, in the preparation of a melt, visible crystals of MnBi are not exposed.

The melt of MnBi and unreacted manganese and bismuth was then pulverized in a high speed hammer mill, yielding irregular particles of approximately 8 microns in diameter. The magnetic MnBi was then separated from unreacted manganese and bismuth by use of a magnetic separator.

The enriched MnBi powder was then hot-pressed at comparatively low pressure (up to 3000 psi) at 300°C in a nonmagnetic cylindrical die with double-acting magnetic rams. The purpose of the field (up to 20 000 oersteds) was to align the particles with their easy direction of magnetization parallel to the direction of testing.

The compacting was performed in a heated die to provide a maximum density at low pressures. In this respect, it is probably desirable to have a small amount of free bismuth present in the powder. This provides a fluid medium at 300°C to facilitate particle alignment and after solidification, upon cooling, effectively separates and immobilizes the particles. Figure 3 illustrates schematically the compaction of the magnets.

TABLE I. X-ray data for MnBi crystals.

Sample	Unit cell length
NOL (quenched from 320°C)	5.87±0.02A
Guillaud (quenched from 400°C)	5.83A
Guillaud (slow cool)	6.11A

Thus, a new class of permanent magnets has been prepared by powder-metallurgy techniques. These magnets exhibit a coercive force (H_c) exceeded by no other known practical magnets. They can be used for practically all present applications of permanent magnets; however, in short lengths, where a high resistance to demagnetization is important, bismanol magnets exceed most commercial permanent magnets in available flux density.

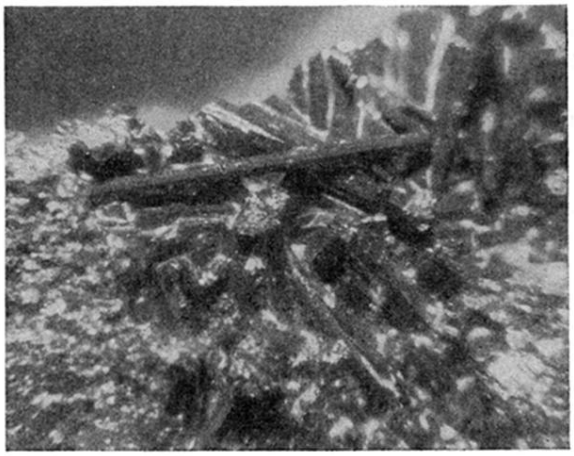

FIG. 2. Hexagonal crystals of MnBi.