DISCUSSION

C. GUILLAUD, *Centre National de la Recherche Scientifique, Bellevue, France:* The manganese-bismuth alloy prepared by Mr. Adams is identical with that which I studied; in fact the characteristic properties of this phase are the same.

I am going to mention the various researches that have led to a new method of attaining high coercive force and to practical magnet construction; then I will summarize the future possibilities.

In 1943[1] I formulated the basic idea that, in a particle of metal or alloy small enough to constitute a single domain, the only possible mechanism is rotation, since no wall displacements can occur without walls. Specifically,[1,2] for a coercive force determined by magnetocrystalline energy I gave the formula $H_c = pK/I_0$ and suggested construction of magnets by use of fine particles with large K. In 1946 Kittel,[3] in an important publication on the properties of fine particles, reached the same conclusions.

In 1947 I pointed[4] out a second cause of high coercive force in fine particles, the magnetoelastic energy, and gave the formula $H_c = p'\lambda\sigma/I_0$ based on a formula of R. Becker. Later Stoner and Wohlfarth[5] arrived at this same mechanism.

Finally, also in 1947, first Néel[6] and then Stoner and Wohlfarth[5] and I[4] gave a third cause of high coercive force, shape anisotropy, which leads to the formula $H_c = p''(N-N')I_0$.

Because of the energy necessary for wall formation and for existence of multidomain grains, the coercive force depends on the grain size; a general study was made in 1946 by Kittel.[3] Furthermore, in aggregates of grains the values of p, p', and p'' depend on the degree of orientation of the domains and on interactions between crystallites. The study of MnBi first gave experimental values of p; later Néel, followed by Stoner and Wohlfarth, perfected the theory and obtained values in good accord with experiment.

The experimental study of these elementary mechanisms is very difficult because it is necessary to separate the effects of the three types of energy. It was our work on MnBi and Mn_2Sb and L. Weil's work on nickel that made possible the clear separation of these effects, by study of the temperature variation of coercive force.

From consideration of rotation in fine particles, the application to magnets follows directly. The high coercive force is determined by one of the three factors mentioned or by several operating simultaneously. Experiments based on magnetocrystalline energy require metals and alloys with large K. Cobalt is of particular interest but so far has yielded unsatisfactory coercive forces—probably because (as L. Weil pointed out and as we have verified) lamellar grains are obtained. Manganese-bismuth magnets based on this mechanism have found industrial application. The possibilities here are far from exhausted.

Use of magnetoelastic energy requires materials with large λ; the internal stresses can then be controlled, for example, by hardening or by formation of solid solutions. Here a great field of research is open.

The possibilities for shape anisotropy are also important. Besides obtaining needle-shaped grains one can seek, for instance, to obtain a ferromagnetic precipitate in needle form within a nonferromagnetic phase, or to improve the usual massive magnets by producing ones composed of oriented crystals with large shape anisotropy.

Rotations against magnetocrystalline and magnetoelastic energy can be produced, not only in aggregates of fine particles, but also by use of holes (as we showed in the study of cobalt ferrites) or of nonmagnetic inclusions in massive materials. These elementary mechanisms have been studied by Kersten and by Néel.

Here is a new path of research on magnets. Practical results have already been obtained, and important progress can be foreseen.

W. SUCKSMITH: *University of Sheffield, England:* We have been investigating the magnetic properties of small iron and cobalt aggregates by utilizing the weakly ferromagnetic copper-rich binary alloys with iron or cobalt. When bulk specimens of these alloys, containing 1–2 percent of cobalt or iron, are quenched from high temperatures, they are paramagnetic, and the curve of intensity against field resembles that of a normal paramagnetic. By heating the alloy at a suitable temperature dependent on constitution, and interrupting this process at appropriate times, the transition from the solid solution to the ferromagnetic two-phase state can be followed in detail. In the initial stages the paramagnetism increases with a decrease in Δ. Later a small but gradually increasing coercivity develops, the I-H curves being quite linear up to $H = 500$ oersteds. At the same time the slope of the curve increases progressively, until the coercivity reaches a maximum value at about 450 oersteds. At this stage it is evident that a harder component is concealed. The remanence, and to a lesser extent the coercivity, increases with the maximum value of the magnetizing field used, even until the latter reaches more than 5000 oersteds. At the same time the reverse field required to decrease the remanence assumes a value considerably

[1] Charles Guillaud, *pli cacheté* deposited March 8, 1943; Compt. rend. **229**, 992 (1949).
[2] Charles Guillaud, thesis (Strasbourg, 1943).
[3] C. Kittel, Phys. Rev. **70**, 965 (1946).
[4] Charles Guillaud, Comm. Soc. franc. de Physique (Strasbourg, May 31, 1947); J. phys. et radium **8**, 347 (1947).
[5] E. C. Stoner and E. P. Wohlfarth, Trans. Roy. Soc. (London) **A240**, 599–642 (1948).
[6] L. Néel, Compt. rend. **224**, 1550 (1947).

in excess of that required to produce a similar effect in a normal ferromagnetic. For example, to reduce the remanence to zero required about 1500 oersteds; to reverse it completely required considerably greater values. At this stage the coercivity begins to fall off; the intensity continues to increase, but with increasing curvature of the *I-H* curve of the familiar shape concave to the field axis. Finally the coercivity falls to a value less than 100 oersteds with the completion of the precipitation process at the temperature employed. It seems evident, not only from the trend of the coercivity-time relationship, but also from the evidence for the concealed harder component of the magnetization, that with continued heat treatment single domain particles increase in size until the appearance of domain walls causes a decrease in coercive force.

L. F. BATES, *University of Nottingham, England:* I would like to draw the authors' attention to some experiments on the ferromagnetic properties of amalgams of iron, nickel, and cobalt in mercury; and in particular to the fact that amalgams of nickel are not ferromagnetic unless they are heated to about 260°C. They may find that experiments on fine particles obtained from the nickel amalgams will be of particular interest.

I should like to mention some experiments which Dr. E. W. Lee made in my department to test the theory of Stoner and Wohlfarth with Alnico. In their paper they assume that single domain particles are embedded in a nonmagnetic matrix, that they are prolate spheroids, and that their magnetic anisotropy is determined solely by their shape. If we assume further that the magnetostriction is isotropic, which is a good approximation as long as there is no regular connection between the crystal axes of the domain material and the axis of the spheroid, we find enough data in Stoner and Wohlfarth's paper to allow us to calculate the magnetostriction of Alnico. This Dr. Lee did.

Dr. Lee's calculation show that the initial magnetostriction should be negative and that there should be no residual magnetostriction. The experimental results for an Alnico with $H_c=133$ oersteds were chosen as most appropriate for comparison with the Stoner and Wohlfarth theory. The negative magnetostriction predicted by that theory was not found, although some Russian workers have recorded it, I understand, with magnetically isotropic Alcomax and Vicalloy.

We feel that if the observed positive magnetostriction is solely caused by islands, then these cannot be of pure iron or of pure cobalt, but might be of iron-cobalt alloy as suggested by Goldman and Smoluchowski.

C. KITTEL, *University of California, Berkeley, California:* The x-ray work of Lipson suggests that fine particles of cobalt have randomly stacked atomic planes. This would have the effect of reducing the crystalline anisotropy energy and therefore the coercive force of a single domain particle. If future x-ray work on fine cobalt particles should bear out this picture, it might be profitable to look for alloying elements which could act as "hexagonalizers" for cobalt.

E. C. STONER, *University of Leeds, England:* The idea that the very high coercivity of certain types of material might be explained in terms of the characteristics of single domain particles occurred to a number of physicists independently at much the same period. In 1939 I made the first calculations with a view to explaining the coercivity of the Alnico type of alloy on the basis of the shape anisotropy of single-domain precipitates of the more strongly ferromagnetic constituent of the alloy. Detailed calculations, equally applicable to shape, crystalline, and strain anisotropy, were resumed and full details published much later.[1] This paper contains the results of the very lengthy analytical and numerical work which is necessary even in the simplest case. Since it is in one of the relatively less accessible journals, attention is directed to it as being of considerable potential usefulness to all those concerned with the relevant alloys and micropowder materials. The extensive and beautiful recent work reported illustrates at once the range of applicability of the basic theoretical treatment and the many additional factors which must be taken into account in actual ferromagnetic materials.

[1] E. C. Stoner and E. P. Wohlfarth, Trans. Roy. Soc. (London) **A240**, 599–642 (1948).