Magnetic Properties of Iron-Cobalt Single Crystals*

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Single crystals of Fe–Co alloys were obtained from recrystallized pure ingots and their components of magnetization parallel to magnetic forces applied along axes of symmetry were measured by a pendulum magnetometer. It was found that the direction for easiest magnetization changes from <100> to <111> as the amount of cobalt in the alloy increases. This transition occurs at about 42 percent Co. This result contradicts Fowler and Powell's view concerning the dependence of direction of magnetization upon crystal structure. Some magnetic properties of polycrystalline alloys are explained. Akulov's theory for the magnetization curve of a single crystal was applied to a specimen with 70 percent Co. The agreement between theory and experiment is good in this case.

IN his theory on the deviation of the direction of magnetization from that of the magnetic field Powell[1] assumes that the interaction between each electron and the atom to which it belongs can be represented by a field G fixed in the crystal. G can have its equivalent maxima in a number of possible directions which are simply related to the crystal structure. By this means the deviation effect can be described both in cubic and non-cubic crystals. Later he and Fowler[2] carried this theory one step further. If the axes of the atomic angular momenta are arranged as required by Powell's theory, then the direction of easiest magnetization will be of the form <100> in iron and of the form <111> in nickel. This is the experimental finding. On this view the direction of easiest magnetization of a substance depends primarily only upon the structure. For instance, any ferromagnetic substance of body-centered cubic structure would be expected to have <100> as the easiest direction.

In order to prove or disprove Fowler and Powell's prediction it is necessary to investigate the magnetic properties of crystals having the same structure as iron, nickel or cobalt but otherwise differing as much as possible. Besides iron-nickel single crystals which have been recently studied by Lichtenberger,[3] iron-cobalt alloys lend themselves to such investigation. The iron-cobalt series has three different structures[4] at room temperature, namely, body-centered cubic lattice from 0 to 78 percent cobalt, face-centered cubic lattice from 78 to 95 percent cobalt, and hexagonal (close-packed) lattice from 95 to 100 percent cobalt. So over the widest range they are of the same structure as iron.

Furthermore, iron-cobalt alloys have some peculiar properties. Over a considerable range of composition they have higher saturation magnetization[5] than either constituent and have large magnetostriction.[6] Alloys of around 50 percent cobalt are easily magnetizable and have high electric conductivity. This shows that some of the iron-cobalt alloys are, in themselves, very interesting ferromagnetic substances.

Very pure iron was obtained from P. P. Cioffi of the Bell Telephone Laboratories, New York and pure cobalt was supplied by the Harshaw Chemical Company, Cleveland, Ohio. The cobalt is found to be 99.37 percent pure and its predominant impurities are iron, manganese and sulphur. Alloys were made in magnesia crucibles in vacuum by means of an induction furnace the coil of which can be gradually raised so that the metal solidifies slowly from the bottom upward. The ingot (50 to 70 grams) obtained in this way contains a large number of small single crystals. In order to make the crystals bigger and more

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[1] F. C. Powell, Proc. Roy Soc. **A130**, 167 (1930).

[2] R. H. Fowler and F. C. Powell, Proc. Camb. Phil. Soc. **27**, 280 (1931).

[3] F. Lichtenberger, Ann. d. Physik [5], **15**, 45 (1932).

[4] R. Ruer and K. Kaneko, Ferrum **2**, 33 (1911); H. Masumoto, Sci. Rep. Tohoku Imp. Univ. **15**, 449 (1926); T. Kasé, ibid. **16**, 491 (1927).

[5] P. Weiss, Trans. Faraday Soc. London **8**, 149 (1912); H. Masumoto, Sci. Rep. Tohoku Imp. Univ. **18**, 195 (1930); G. W. Elmen, J. Frank. Inst. **207**, 583 (1929); A. Kussmann, B. Scharnow and A. Schulze, Zeits. f. techn. Physik **13**, 449 (1932).

[6] S. R. Williams, Rev. Sci. Inst. **3**, 675 (1932); Y. Masiyama, Sci. Rep. Tohoku Imp. Univ. **21**, 394 (1932).

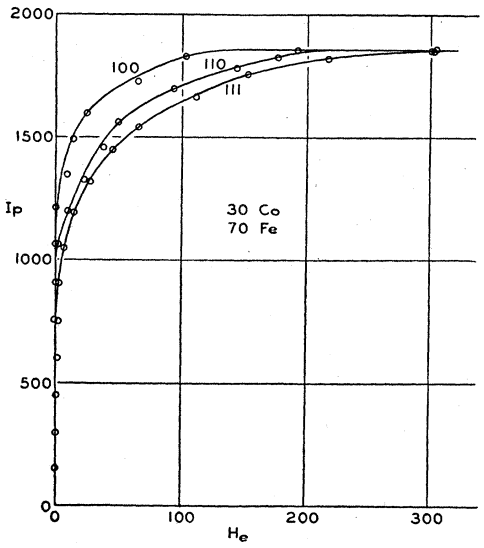

FIG. 1. I_p—*vs.*—H_e for 30 percent Co.

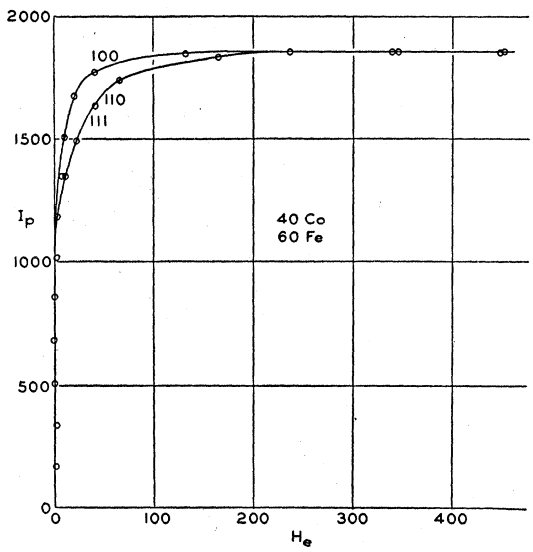

FIG. 2. I_p—*vs.*—H_e for 40 percent Co.

perfect the ingot was annealed in a resistance furnace in an atmosphere of hydrogen for several hours. The annealing temperature was not higher than 50°C above the allotropic transformation point (above which the alloys have a face-centered cubic structure) and the rate of cooling was about 4 or 5°C per minute.

The recrystallized ingot was etched with nitric acid in alcohol as usual and the etch plane is of the form {100}. In order to cut a specimen in a certain crystallographic plane the orientation of the selected crystal was determined by means of a goniometer with a Gauss eyepiece. An oblate spheroid with its axis of rotation parallel to a <110> direction was carefully prepared by means of a new and accurate method.[7] It was then annealed in hydrogen for two hours at a temperature about 50°C below its transformation point. The final step before deciding that a spheroid was fit for magnetic measurements was to take a Laue photograph to determine its crystal axes. The results of the x-ray analysis and some other constants of the specimen are given in Table I. In this table, N denotes the demagnetizing factor for the equatorial plane computed from the formula

$$N=2\pi\left[\frac{(1-e^2)^{\frac{1}{2}}}{e^3}\sin^{-1}e-\frac{1-e^2}{e^2}\right],$$

[7] L. W. McKeehan, Rev. Sci. Inst. (Aug.) (1934).

TABLE I. *Constants of specimens.*

Percent Co by synthesis	Assumed $\alpha-\gamma$ Temp.	Vol. cm³	Thickness cm	Diameter cm	N	α	β
30	950°C	.001114	.024	0.299	0.718	45°	7°
40	970°C	.001535	.025	0.350	0.635*	40°	0
50	960°C	.00180	.0238	0.360	0.601	45°	0
70	860°C	.001559	.0244	0.343	0.644	40°	0

* Calculated value is 0.646 but 0.635 is the highest value which fits the data.

where e is the eccentricity of the generating ellipse, α the angle between the axis of rotation of the spheroid and one of the four-fold crystal axes and β the angle between this axis and a {001} plane which contains the said four-fold axis. (α is 45° and β is 0° for a perfectly cut specimen.) The crystals are more or less imperfect as shown by the irregularity of Laue spots. This may be due to alloying or to mechanical disturbance during the process of shaping. Since we are interested in the general features of the magnetization curve these small imperfections have been ignored.

For magnetic measurement a pendulum magnetometer[7] was constructed. It is especially suitable for small crystal specimens and has some advantages over Weiss's torsion magnetometers. The results of measurement are plotted in Figs. 1

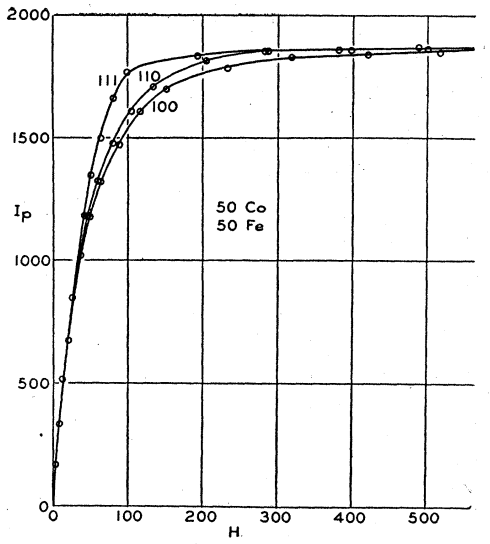

FIG. 3. I_p—*vs.*—H_e for 50 percent Co.

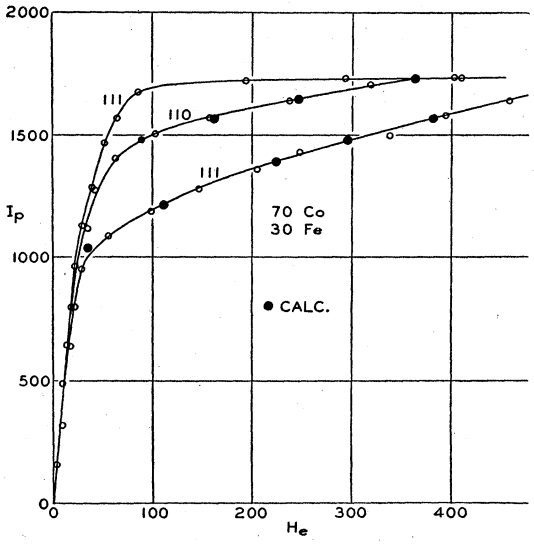

FIG. 4. I_p—*vs.*—H_e for 70 percent Co.

to 4. In these figures I_p denotes the component of magnetization parallel to the applied magnetic field and H_e the field corrected for the demagnetizing effect. H_e is hardly to be distinguished from 0 up to a considerable value of I_p. The probable error in the absolute measurement is about 1.6 percent of which about 1 percent is due to the error in weighing the specimen. Relative measurements on a single specimen are more precise.

We see that the direction of easiest magnetization depends upon the amount of cobalt in the alloy. The alloys we measured are all of body-centered cubic lattice but those of 30 and 40 percent Co have <100> those of 50 and 70 percent Co have <111> as the easiest direction. This indicates that the direction for easiest magnetization does not depend merely upon the crystal structure and does depend upon the kind of atoms of which the crystal consists, contradicting Powell and Fowler's prediction.

The shift of the direction of easiest magnetization in our alloys is similar to that already found in the iron-nickel system by Lichtenberger.[3] From 33 to 100 percent nickel Fe-Ni alloys are of face-centered cubic lattice. The direction for easiest magnetization changes in this range from <100> as in iron to <111> as in nickel, the transition occurring at about 71 percent nickel. Lichtenberger was not able to fix this point very accurately.

The magnetic energy input per unit volume is represented by the area included between an $I-H$ curve and the I-axis up to any value of I. Part of this is stored and part is dissipated in hysteresis. Since in our case the hysteresis effect is negligibly small the energy difference for magnetization along different symmetry axes may be taken as the area included between the two $I-H$ curves under consideration. These energy differences are given in Table II.

TABLE II. *Energy differences.*

Percent Co	$W_{111}-W_{100}$ erg. cm^{-3}	$W_{110}-W_{100}$ erg. cm^{-3}
30	0.38×10^5	0.24×10^5
40	0.11 "	0.11 "
50	−0.37 "	−0.17 "
70	−1.41 "	−1.05 "

Fig. 5 shows how the composition for $W_{111}-W_{100}=0$ is graphically obtained.[8] We see that the curve cuts the concentration axis at about 42 percent Co. This agrees well with the findings[5] that the polycrystalline alloy with about 40 percent cobalt has maximum initial permea-

[8] The point for iron is derived from measurements by K. Honda and S. Kaya, Sci. Rep. Tohoku Imp. Univ. **15**, 721 (1926).

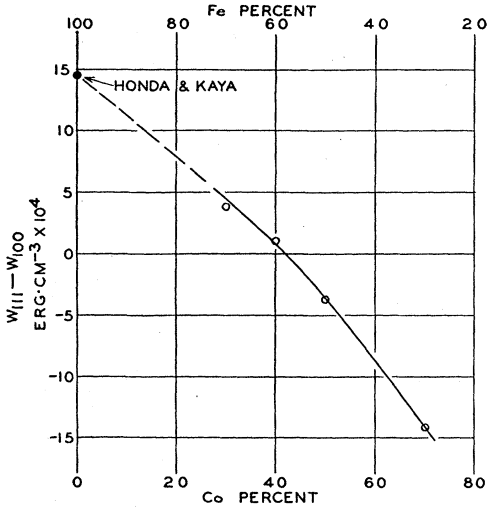

FIG. 5. $W_{111}-W_{110}$—*vs.*—composition.

bility and that an alloy with 50 percent has maximum intrinsic induction in low field. Alloys in this range of composition will be expected to contain elementary crystals which are easily magnetized in all directions. In a comparative high field this effect will be relatively less important so that the magnetization-concentration curve becomes flatter for higher applied field intensities.

Although our maximum magnetizing field is not very high the magnetization is seen to attain nearly to the saturation value. The 30, 40 and 50 percent alloys have practically the same saturation value (I_∞). Weiss[5] and Masumoto[5] found a maximum I_∞ for 34 percent Co alloy while Elmen[5] places the maximum at 50 percent. Recently Kussmann, Scharnow and Schulze[5] obtained about the same limiting magnetization over the range from 30.9 to 52.4 percent Co and maximum electric conductivity at around 50 percent Co instead of at 60 percent as found by Elmen. Kussmann and his co-workers conclude that in the alloy with 50 percent Co the atoms are more or less in an ordered state so that the metallic compound FeCo may be said to exist. Weiss much earlier proposed the existence of a compound Fe_2Co, and Elmen suggests $FeCo_2$. The formula FeCo corresponds to 48 percent Co by weight. Our results on the direction of magnetization apparently support Kussmann's view.

In the case of nickel and cobalt[9] crystals Akulov's[10] theory of the magnetization curve of single crystals does not agree with experimental results so well as it does in the case of iron. It is interesting to see how his theory works for iron-cobalt crystals. Let us consider first the 70 percent Co crystal which has $<111>$ as the direction for easiest magnetization. Following Akulov's method we find that

$$H_{110}=H_{111}+(2K/I_\infty)(I_{110}/I_\infty)[2-3(I_{110}/I_\infty)^2]$$

and

$$H_{100}=H_{111}+(2K/I_\infty)(I_{100}/I_\infty)[1-3(I_{100}/I_\infty)^2],$$

where H_{hkl} and I_{hkl} are, respectively, the magnetic field and magnetization along the direction $<hkl>$. I_∞ is the saturation value of magnetization, K is a material constant which may be computed from the equation $W_{111}-W_{100}=2K/3$. $W_{111}-W_{100}$ is here found to be -1.41×10^5 ergs·cm^{-3}. Hence K is equal to -2.13×10^5 ergs·cm^{-3}. By assigning different values to I_{hkl}, we can compute corresponding values of H_{hkl}. These pairs of I, H, values are represented by the black circles in Fig. 4. The good agreement between theory and experiment is to be expected because Akulov's theory should apply only in cases where there is no hysteresis. This is nearly true in the present case, the maximum hysteresis work per cycle (not accurately measurable) being estimated to be less than 7×10^3 ergs·cm^{-3} for the hardest specimen, that with 70 percent Co. The theory is less satisfactory for an alloy with 40 percent Co where two of the three $I-H$ curves for different axes are indistinguishable. No single value of K can account for such behavior.

In conclusion, the author wishes to express his thanks to Professor L. W. McKeehan for suggesting this problem and for his advice and encouragement during the investigation. He is also indebted to Professor W. E. Milligan of the Hammond Laboratory for making chemical analysis of cobalt, and to the China Foundation, Peiping, China for their financial help in 1932 and 1933.

[9] F. Bitter, Phys. Rev. **38**, 528 (1931).
[10] N. Akulov, Zeits. f. Physik **67**, 794 (1931); **69**, 78 (1931).