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journal or publication title	Science reports of the Research Institutes, Tohoku University. Ser. A, Physics, chemistry and metallurgy
volume	6
page range	539-550
year	1954
URL	http://hdl.handle.net/10097/26668

Magnetic Hysteresis in Annealed Nickel-Cobalt Alloys*

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(Received July 23, 1954)

Synopsis

The magnetic hysteresis loops have been determined ballistically on annealed nickel-cobalt alloys covering the whole composition range, and their shape, remanence (I_R), and coercive force (H_C) have been studied. Generally, the hysteresis loops of γ-phase (face-centred cubic) alloys are narrow (low H_C) and steep (high I_R), those of ε-phase (close-packed hexagonal) alloys are wide (high H_C) and flat (low I_R), and those of $\gamma+\varepsilon$-phase alloys are intermediate between the two former. The hysteresis loops of γ-phase alloys containing more than about 25 percent cobalt usually take an abnormal shape like those of perminvars and permalloys. It is pointed out that such abnormal hysteresis loops may be explained by the occurence of an additional uniaxial anisotropy along the direction of magnetization vectors during annealing, which may also be responsible for the effect of magnetic annealing on ferromagnetic solid solutions, as noted recently by us(1).

The observed I_R values for γ-phase alloys are shown to lie between the two extreme theoretical values derived assuming either that all of the directions of easy magnetization in every crystal grains are energetically isotropic or that only one of them is preferred. H_C as a function of the composition is discussed in terms of the magnetocrystalline anisotropy, magnetoelastic energy and induced uniaxial anisotropy. It is also pointed out that both I_R and H_C in ε-phase alloys may be influenced by the presence of free magnetic poles at grain boundaries.

I. Introduction

Previously, one of the authors(2) studied the initial magnetization curves and their characteristics, namely, the initial and maximum susceptibilities, saturation magnetization and field, and magnetocrystalline anisotropy constant, as functions of the composition and constitution, with annealed nickel-cobalt alloys covering the whole composition range. The present paper as a continuation from the preceding one(2) concerns with the investigation of the magnetic hysteresis loops and their characteristics, namely, the remanence, I_R, and coercive force, H_C, of the same alloys, of which only a few scattered data(3, 4) was available.

The specimens employed are the same as those used in the previous investigation(2) and their compositions are shown in Table 1. They are circular cylinders, most of them being 3 mm in diameter and 10 cm in length, and annealed at 1000°C for 2 hours. The measurements have been made with the ballistic-galvanometer method

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* The 774th report of the Research Institute for Iron, Steel and Other Metals.

(1) S. Taniguchi and M. Yamamoto, Sci. Rep. RITU, **A6** (1954), 330.

(2) M. Yamamoto, Nippon Kinzoku Gakkai-shi, **11** (1947), No. 11~12 (p. 3); **13** (1949), No. 6 (p. 15) (in Japanese); Sci. Rep. RITU, **A4** (1952), 14.

(3) A. Kussmann and B. Sharnow, in W. S. Messkin-A. Kussmann, *Die Ferromagnetische Legierungen*, Berlin (1932), p. 85; Gumlich, Steinhaus, Kussmann and Scharnow, ibid., p. 133.

(4) See, R. M. Bozorth, *Ferromagnetism*, D. van Nostland, New York, (1951), p. 276.

at room temperature using a water-jacketed magnetizing coil of about 40 cm long and of the constant of 57.7 Oe/A. The maximum effective field, H_m, is about 500 oersteds, with a few exceptions especially noted.

Table 1. Composition of nickel-cobalt specimens used, the measured data of the remanence (I_R), coercive force (H_C), and saturation magnetization (I_S).

No.	Specimen mark	Composition wt.-% Co	I_R	I_S(2)	H_C Oe
1	N1b	0.60	218	496	0.93
2	P1c	1.87	264	516	0.51
3	P1d	1.87	247	514	0.56
4	N2a	3.0	238	525	2.14
5	NN1a	4.2	250	538	1.21
6	NN2c	5.5	221	551	0.34
7	NN2b	5.9	201	555	0.41
8	N3b	6.0	348	552	2.01
9	N3d	6.21	368	558	1.66
10	SN7a	8.4	313	581	1.83
11	SN7b	9.0	272	587	0.65
12	NN3f	12.51	293	625	0.23
13	N6a	15.20	273	647	0.39
14	N6b	15.20	257	648	0.16
15	SN8c	18.3	197	683	0.70
16	3a	21.0	241	711	0.65
17	N7a	23.5	225	737	0.88
18	4a	31.3	277	817	1.10
19	5a	40.6	180	903	1.45
20	7a	49.56	189	983	1.92
21	N9d	55.5	218	1038	1.83
22	8a	59.1	228	1071	1.40
23	SN1b	67.5	260	1146	1.04
24	9a	68.95	179 199*	1158**	7.46 7.88*
25	10b	75.09	142	1213**	15.7
26	11a	80.04	107	1257**	19.6
27	12b	85.01	117	1301**	24.2
28	14b	94.80	121	1389**	27.5
29	N16c	98.24	138	1419**	30.2
30	15b	99.86	125 146*	1434**	34.1 38.0*

* Data for the maximum field of 1100 Oe.

** Determined from the empirical formula $I_S=542+8.93C$ for $C \geq 34.6$ wt.-% Co.(2)

In addition to the above-mentioned general magnetic properties(2), the density(5), longitudinal magnetostriction(6), Young's modulus(7), and ΔE-effect(7) were already measured with the same specimens by one of the authors and his collaborators, and their results have unanimously indicated that the composition range up to about 68 percent cobalt is occupied by the γ (face-centred cubic) phase, the range from 78 to 100 percent cobalt is occupied by the ε (close-packed hexagonal) phase and the remaining relatively wide range is occupied by the mixture of the two phases.

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(5) M. Yamamoto, Nippon Kinzoku Gakkai-shi, **11** (1947), No. 11-12 (in Japanese); Sci. Rep. RITU, **A2** (1950), 871.

(6) M. Yamamoto and R. Miyasawa, Nippon Kinzoku Gakkai-shi, **B15** (1951), 505 (in Japanese); Sci. Rep. RITU, **A5** (1953), 22.

(7) M. Yamamoto, Nippon Kinzoku Gakkai-shi, **12** (1948), No. 2-3; M. Yamamoto and S. Taniguchi, ibid., **B15** (1951), 337 (both in Japanese).

II. Magnetic hysteresis loops

To give a general view of the magnetic hysteresis loops of annealed nickel-cobalt alloys, the typical ones are shown in Figs. 1(a)~(d). As was expected from the shape of the initial magnetization curves(2), the hvsteresis loops of γ-phase alloys are generally narrow (H_C is low) and steep (I_R is high), those of ε-phase alloys are wide (H_C is high) and flat (I_R is low), and those of two-phase alloys are intermediate between the two former. It is to be noted that the hysteresis loops of γ-phase alloys containing more than about 25 percent cobalt usually take an abnormal shape as shown in Figs. 1 (b) and 2.

The whole aspects of the hysteresis loops of nickel, cobalt, and 69 %Co alloy belonging to the two-phase region are shown in Fig. 1(d), in which H_m is 1100 oersteds for the loops of cobalt and 69 %Co alloy. As may be seen from this figure, the magnetization of γ-phase alloys is near to saturation and consequently

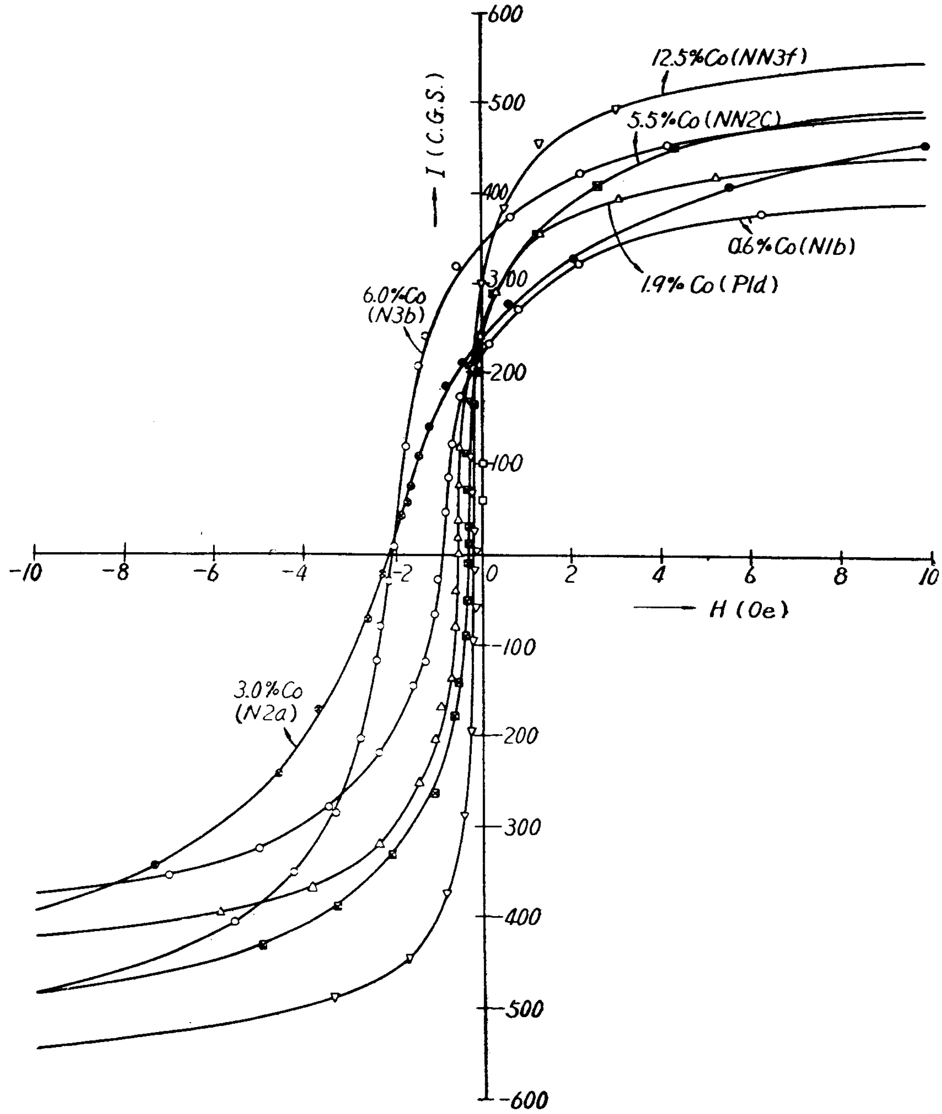

Fig. 1 (a). Descending branches of hysteresis loops for the maximum field of 500 oersteds of γ-phase nickel-cobalt alloys containing less than 12.5 percent cobalt.

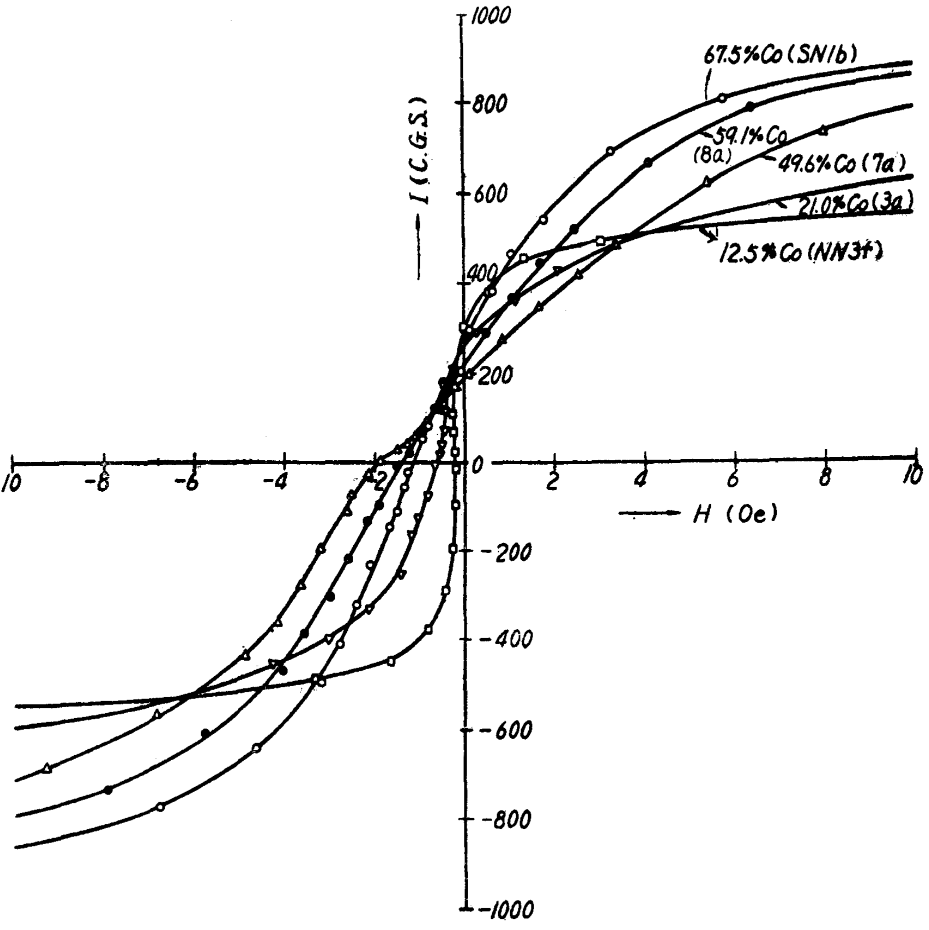

Fig. 1 (b). Descending branches of hysteresis loops for the maximum field of 500 oersteds of γ-phase nickel-cobalt alloys containing more than 12.5 percent cobalt.

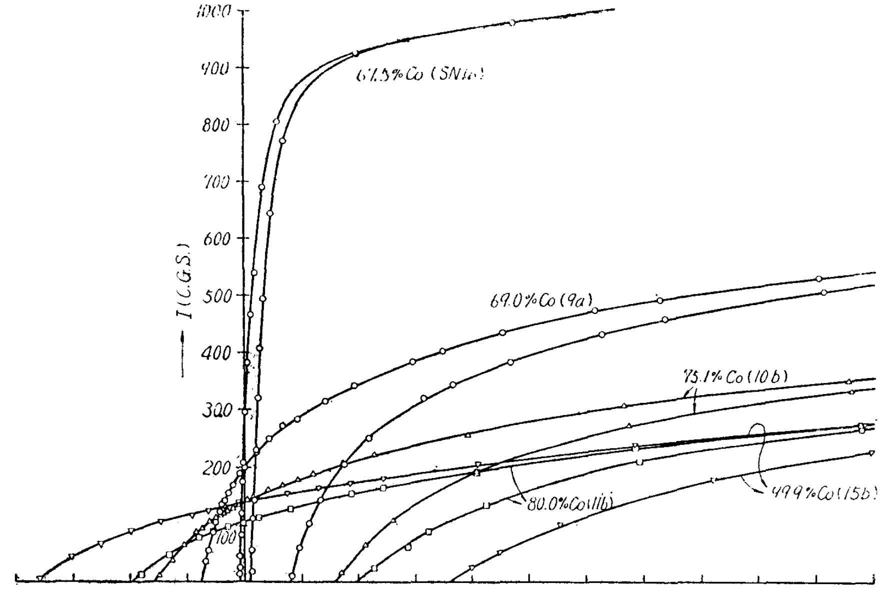

Fig. 1 (c). Hysteresis loops for the maximum field of 500 oersteds of two-phase and ε-phase nickel-cobalt alloys. The loop of a γ-phase nickel-cabalt alloy containing 67.5 percent cobalt is also plotted for comparison.

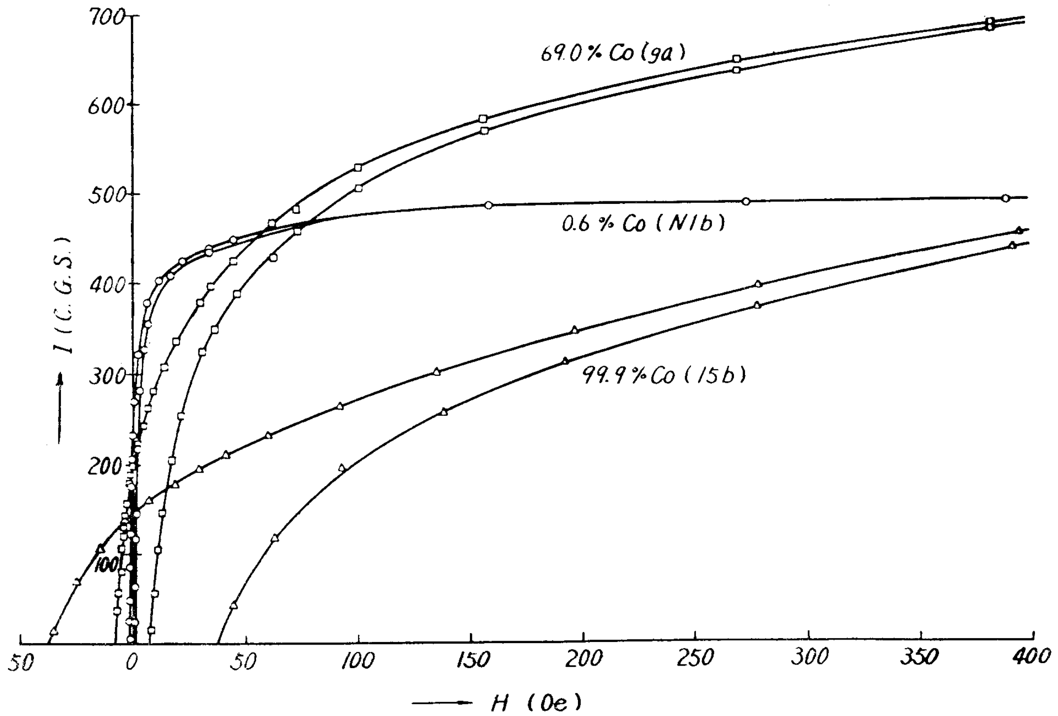

Fig. 1 (d). Hysteresis loop for the maximum field of 500 oersteds of nickel and the loops for the maximum field of 1100 oersteds of cobalt and of a two-phase nickel-cobalt alloy containing 69.0 percent cobalt.

shows no hysteresis at about 500 oersteds, while the magnetization of $\gamma+\varepsilon$-phase and ε-phase alloys is far from saturation but shows a fairly small hysteresis at this field strength. Thus, the remanence and coercive force for $H_m = 500$ Oe may be regarded as the retentivity and coercivity with no appreciable error (within the limits of error of 5 percent for $\gamma+\varepsilon$-phase alloys and of 10 percent for ε-phase alloys).

III. Abnormal hysteresis loops of high-cobalt γ-phase alloys and their origin

As noted above, the hysteresis loops of annealed γ-phase alloys containing more than about 25 percent cobalt are usually abnormal and take the so-called "constricted form" (see Figs. 1(b) and 2). It is already well known that such an abnormal hysteresis loop is revealed by annealed perminvars(8) and permalloys(9), which show, moreover, the constant permeability at low fields and the effect of the annealing in magnetic field.

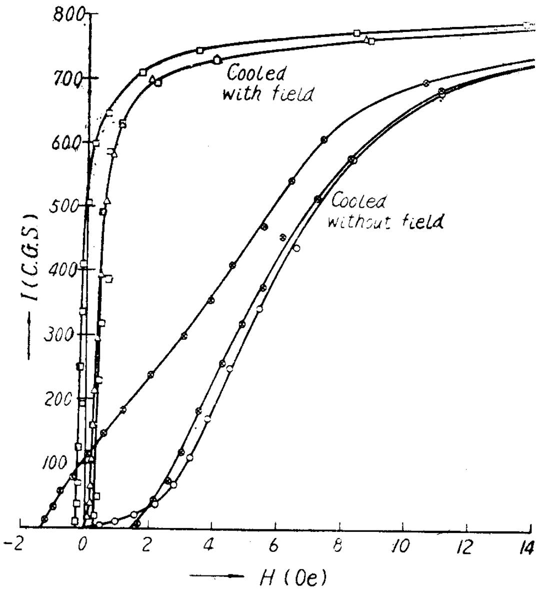

Fig. 2. Effect of the field cooling (37 Oe; 200°C/hr) on the magnetic properties of a nickel-cobalt alloy containing 40.6 percent cobalt (5a).

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(8) For example, see R. M. Bozorth, *Ferromagnetism*, D. Van Nostland, New York, (1951), pp. 163~180.

(9) T. Nagashima, Ôyô Butsuri (J. App. Phys. Japan), **19** (1950), 53 (in Japanese).

High-cobalt γ-phase nickel-cobalt alloys also show all of these characteristics, as shown in Figs. 2 and 3(10). The origin of these characteristics has so far been thought to be associated with the presence of a superlattice(11), but recent studies by the present authors indicate that any superlattice cannot be detected in nickel-cobalt alloys(12) and, further, that these properties are really common in ferromagnetic solid solutions(1,13), as the following brief description shows.

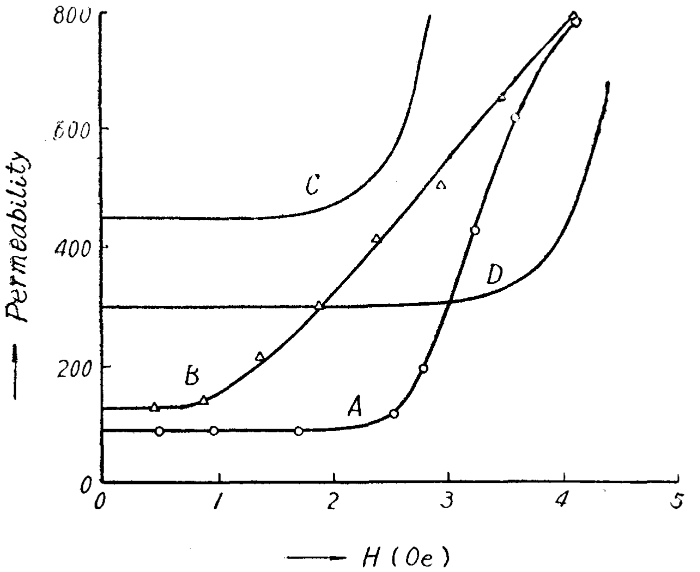

Fig. 3. Permeability curves before and after the alternating-current demagnetization (A and B) of an annealed nickel-cobalt alloy containing 55.5 percent cobalt (N9d), as compared with the curves, presumably before the A. C. demagnetization, of 45–25 perminvar as annealed (C) and baked (D), obtained by Elmen.

In a ferromagnetic substance, there exists, besides the ordinary isotropic exchange interactions, the anisotropic interaction due to the interplay between the spin-orbit interaction and orbital valence, which may be expressed approximately by dipole-dipole and quadrupole-quadrupol interactions and may be the main origin of the magnetocrystalline anisotropy in cubic crystals(14). In a ferromagnetic solid solution, the anisotropic interaction depends on the kind of atom pairs as well as on the direction of spontaneous magnetization with respect to the crystallographic axes, so that the equilibrium distribution of solute atom pairs become anisotropic below the Curie temperature. This anisotropic distribution of solute atom pairs, in turn, generates an additional uniaxial ferromagnetic anisotropy. Thus, the direction of the spontaneous magnetization may be stabilized during annealing.

In a face-centred cubic solid solution such as γ-phase nickel-cobalt alloys, both 180° and non$-$180° domain walls may be stabilized by this mechanism, irrespective of the sign of the cubic anisotropy(13). Since this stabilization becomes very strong at high solute concentrations, every non$-$180° wall displaces almost reversibly, but 180° walls displace irreversibly. Hence, the remanence is far smaller than that without this stabilization and the coercive force is determined by the irreversible character of 180° walls. This is a brief explanation for the abnormal magnetic properties of perminvars, permalloys, and high-cobalt face-centered cubic nickel-

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(10) The effect of the magnetic annealing in nickel-cobalt alloys has also been studied by H. Masumoto *et al.*, Nippon Kinzoku Gakkai-shi, **17** (1953), 607, 612 (in Japanese); Sci. Rep. RITU, **A6** (1954), 375.

(11) S. Kaya, Rev. Mod. Phys., **25** (1953), 49.

(12) S. Taniguchi and M. Yamamoto, to be published.

(13) S. Taniguchi, to be published.

(14) J. H. Van Vleck, Phys. Rev., **52** (1937), 1178.

cobalt alloys. As to the effect of the magnetic field applied during annealing, it is sufficient to consider the fact that the applied field high enough for saturation induces the uniaxial anisotropy along its direction and the stabilization of walls cannot occur.

IV. The Remanence

The observed values of remanence, I_R, are given in Table 1, and the ratio of I_R to the saturation magnetization, I_R/I_S, as a function of the composition is shown in Fig. 4. The relation between I_R/I_S, and composition in γ-phase alloys is unexpectedly complicated; I_R/I_S starting from 0.45 for nickel makes three maxima and three minima sucssessively and eventually attains to a small value of about 0.2.

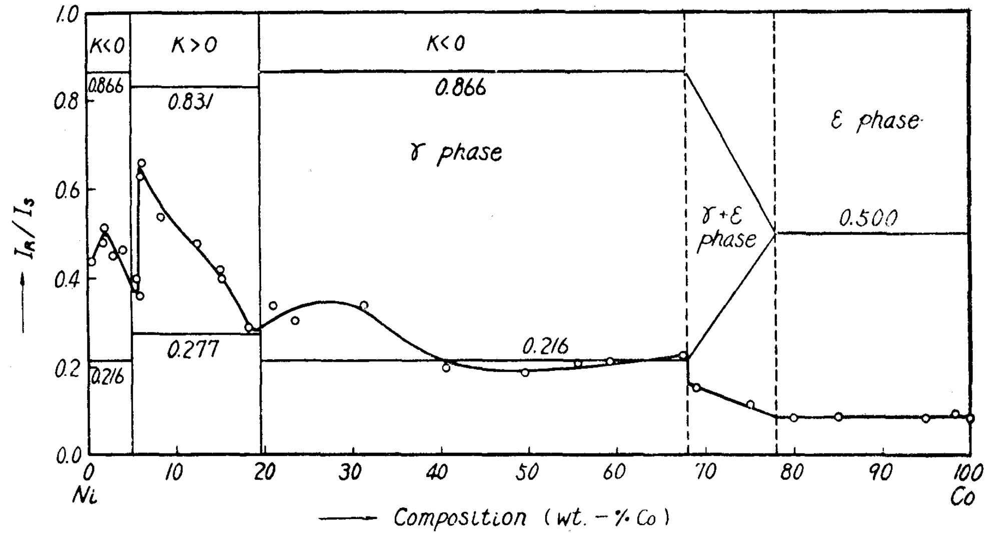

Fig. 4. Ratio of the retentivity to the saturation magnetization as a function of the composition in nickel-cobalt alloys. The two vertical dotted lines mark the phase boundaries and the two vertical full lines in the γ-phase range mark the compositions where the magnetocrystalline anisotropy constant, K, passes through zero.

On the whole, I_R/I_S is low in γ-phase alloys and even the highest value is only about 0.65 at the second maximum. The first minimum (0.35) and the second one (0.28) occur at 5 and 20 percent cobalt, respectively. The third, particularly wide and flat, minimum is lowest (about 0.2) and occupies the composition range showing the above-mentioned abnormal hysteresis loops. It is to be noted that the first maximum is not so obvious as the others because of the scatter of the observed points.

I_R/I_S decreases abruptly from 0.23 to 0.17 at the boundary between the γ-phase and $\gamma+\varepsilon$-phase regions (about 68 percent cobalt), then decreases linearly in the $\gamma+\varepsilon$-phase region and finally takes a very low and constant value of about 0.09 in the ε-phase region.

Now, let us consider a ferromagnetic cubic polycrystal composed of equiaxed crystal grains oriented at random and having small internal stress (this is not merely mechanical stress but means the origin of any additional magnetic anisotropy in a broad sense). When the magnetization reduces from saturation, the magnetization vectors in each grain may generally rotate towards the direction of easy magnetization nearest to the applied field, if the magnetocrystalline anisotropy energy predominates over the magnetic strain energy. Then, I_R/I_S should be 0.831(15) or 0.866(16) according to whether the ferromagnetic anisotropy constant, K, is positive or negative, if all of the directions of easy magnetization in each grain are equivalent energetically. However, when the internal mechanical stress or above-mentioned induced uniaxial anisotropy favores one of the directions of easy magnetization, I_R/I_S becomes $(1/3)\times 0.831$(17) and $(1/4)\times 0.866$ according to the sign of K. Because, when the direction of easy magnetization nearest to that of magnetizing field is not favored, the magnetization vectors at first rotate towards that direction as the field decreases and then turns over to the favored direction of easy magnetization by the displacements of non-180° domain walls, and since the probabilities that the magnetization vectors direct in one sense and in the opposite sence of the favoured direction of easy magnetization are equal, the contributions to the remanence from these magnetization vectors cancel out in the specimen as a whole. Hence, the net contribution to the remanence is due to the magnetization vectors which orient in the favoured direction of easy magnetization nearest to the magnetizing field, and the probability that the directions of easy magnetization nearest to the direction of applied field is favoured is 1/3 or 1/4 according to the sign of K. It is to be noted, however, that even in such cases, some finite energy is required to displace the non-180° domain walls because of the local fluctuation in the wall energy, so that I_R/I_S cannot be expected to become exactly $(1/3)\times 0.831$ or $(1/4)\times 0.866$. Thus, it is to be expected that I_R/I_S lies between the two extreme values.

In fact, the observed values of I_R/I_S for γ-phase alloys, on the whole, locate between the two extreme values, as seen from Fig. 4. The first and the second minima at 5 and 20 percent cobalt may be due to the fact that the domain wall displacements are easy in these alloys since the magnetocrystalline anisotropy constant passes through zero at these compositions(18) (Fig. 5(2)). While, the third minimum centered at about 50 percent cobalt may be ascribed to the stabilization of domain walls as mentioned in III. As the induced uniaxial anisotropy increases in proportion to the square of the solute concentration and attains a maximum value of the orders of 10^3 erg/cm^3 or more at 50 percent of solute concentration(1, 19), the effect of stabilization of domain walls by the indued uniaxial anisotropy on I_R/I_S should become most pronounced at this composition.

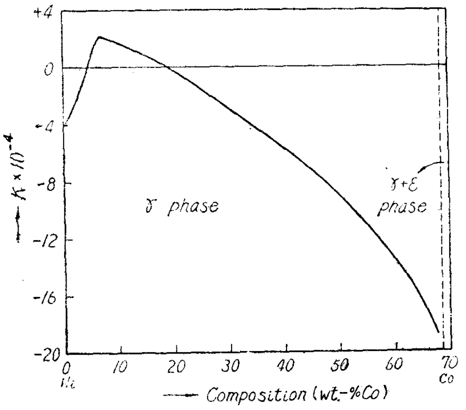

Fig. 5. Magnetocrystalline anisotropy constant, K, as a function of the composition in face-centred cubic (γ-phase) nickel-cobalt alloys (after Yamamoto(2)).

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(15) See, R. Becker and W. Doring, *Ferromagnetismus*, Springer, Berlin (1939), p. 287.

(16) M. Yamamoto and R. Miyasawa, Nippon Kinzoku Gakkai-shi, **B15** (1951), 509 (in Japanese); Sci. Rep. RITU, **A5** (1953), 113.

(17) R. M. Bozorth, Z. Phys., **124** (1948), 519; S. Chikazumi, J. Phys. Soc. Japan, **5** (1950), 327.

(18) J. W. Shih, Phys. Rev., **50** (1936), 376; L. W. McKeehan, Phys. Rev., **51** (1937), 136; M. Yamamoto, reference (2).

(19) S. Taniguchi, to be published.

It is to be noted, however, that at low-cobalt concentrations, the energy difference among the directions of easy magnetization may rather be due to the internal mechanical stress.

It may be readily shown that the ratio of the retentivity to the saturation magnetization for polycrystals having the proper uniaxial ferromagnetic anisotropy must be 0.5, but the observed values of about 0.09 for cobalt and ε-phase alloys are far smaller than this theoretical value. In polycrystalline cobalt and ε-phase alloys, the density of free magnetic poles appearing at grain boundaries may be so high that the demagnetization field due to these free poles may cause the reverse magnetization and make the retentivity smaller than $0.5I_S$. The detailed consideration about the effect of free magnetic poles at grain boundaries on the magnetic properties will given in a later paper.

Finally, the abrupt decrease in I_R/I_S at the phase boundary between the γ-phase and $\gamma+\varepsilon$-phase regions may be due to the influence of the uniaxial magnetic properties of transformed ε-phase and of the volume change accompanied by the $\gamma \rightarrow \varepsilon$ transformation. Similar abrupt changes at this phase boundary have been found in the density(5), Young's modulus(7), ΔE-effect(7), magnetic susceptibilities(2), and magnetostriction(6), and also in the coercive force, as will be shown in the next section.

V. The coercive force

The observed values of the coercive force, H_C, are given in Table 1 and plotted as a function of composition in Fig. 6. Similar to the remanence, the composition-dependence of H_C in the γ-phase region is very complicated and shows three maxima and three minima. The maximum values, however, reach no more than two oersteds. After increasing abruptly to about six oersteds at the boundary between the γ-phase and two-phase regions, H_C increases linearely in the two-phase region reaching to about 20 oersteds, and further it increases linearly again in the ε-phase region, attaining to about 30 oersteds at 100 percent cobalt.

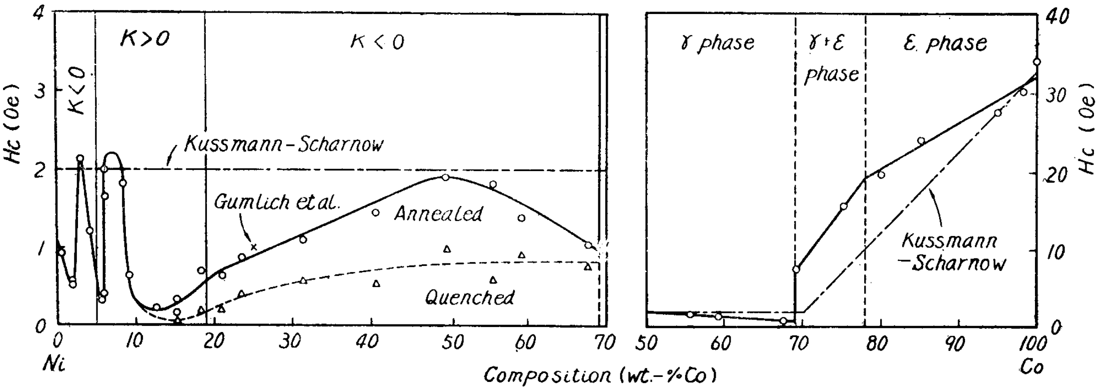

Fig. 6. Coercivity, H_C, as a function of the composition in nickel-cobalt alloys both in annealed and in quenched states. Vertical dotted lines mark the phase boundaries and the two vertical full lines in the γ-phase region mark the compositions where the magnetocrystalline anisotropy constant, K, passes through zero.

Generally speaking, the coercive force may eventnally be determined by the maximum value of the change in the wall energy with position of the wall,

$(d\gamma/dx)_{max}$, as

$$H_C = k(d\gamma/dx)_{max}/I_S \ , \qquad (1)$$

where k is a constant dependent only on the kind of the wall and on the direction of the applied field. Eq. (1) may be rewritten as(20)

$$H_C \approx p_c\lambda_e\sigma_i/I_S \ , \qquad (2)$$

where λ_e is the saturation magnetostriction along the direction of easy magnetization, σ_i is the amplitude of internal mechanical stress, and p_c is a numerical factor dependent on the wave length of internal mechanical stress, l, and on the wall thickness, δ. p_c equals 1 for $l \approx d$ and becomes very small both for $l \ll \delta$ and $l \gg \delta$. Since the internal mechanical stress may be considered to be small in the annealed state, the wall thickness, δ, may be determined by the ferromagnetic anisotropy constant, K, as

$$\delta \propto \sqrt{A/|K|} \ , \qquad (3)$$

where A is the constant of the exchange energy density. Accordingly, if $|K|$ changes from a large value towards zero, p_c would become maximum at a certain value of $|K|$.

As seen from Eq. (2), the maximum of H_C may be determined by the maximum of p_c, when both λ_e and I_S change monotoneously with composition and σ_i can be considered nearly constant, as in annealed nickel-cobalt alloys(2, 7). On the other hand, as seen from Fig. 5. K changes its sign from negative to positive at about 5 percent cobalt and then from positive to negative at about 20 percent cobalt. Therefore, two minima at compositions where K changes its sign and four maxima around them may be excepted to appear in H_C. Two minima of H_C at about 5 and 15 percent cobalt in Fig. 6 correspond to the theoretically expected ones. The maximum of H_C at about 3 percent cobalt in Fig. 6 corresponds to the first maximum of p_c, and that at about 7 percent cobalt corresponds to the overlapping of the second and third maxima of p_c. The fourth maximum of H_C may be expected to appear at about 25 percent cobalt, but, as seen in Fig. 6, it really does not appear, because of its location in the composition range showing the abnormal hysteresis loops mentioned in III.

According to the just-mentioned considerations, H_C must decrease gradually beyond about 25 percent cobalt, but really it increases and reaches a maximum at about 50 percent cobalt. This maximum may be due to the stabilization of domain walls by the induced uniaxial anisotropy, described in III, and that it locates at 50 percent cobalt, means the stabilization or the induced uniaxial anisotropy is maximum at this composition. This has been verified by the fact that H_C in quenched state does not show maximum and is smaller than that in annealed state, as shown in Fig. 6(12).

The origin of the observed minimum at about 2 percent cobalt may be uncertain. Also, it is to be noted that, according to the experimental results obtained by one of the authors (Yamamoto) and Miyasawa(6) on the longitudinal magnetostriction of annealed nickel-cobalt alloys, the field strength where the magnetostriction begins to appear is almost the same as H_C in the composition range from about 10 to 70 percent cobalt.

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(20) C.f. R. Becker and W. Döring, *Ferromagnetismus*, Springer, Berlin, (1939).

The coercive force of a ferromagnetic polycrystal having only one direction of easy magnetization like cobalt may be influenced by the presence of magnetic free poles at grain boundaries as in the remanence, since the demagnetizing field due to these free poles weakens the applied magnetic field so that the field strength corresponding to $(d\gamma/dx)_{max}$ may increase.

Finally, the relation between the initial susceptibility, χ_0, and coercive force may be given by a formula(21)

$$\chi_0 \propto I_S/H_C \, , \qquad (4)$$

which means that the low coercive force corresponds to the high initial susceptibility. The relation between the initial susceptibility and composition in annealed nickel-cobalt alloys as obtained by one of the authors (Yamamoto)(2)(Fig. 7) show indeed a behavior entirely inverse to the composition-dependence of the coercive force.

The results of measurement obtained by Kussmann and his coworkers(3) are also slown for comparison in Fig. 6.

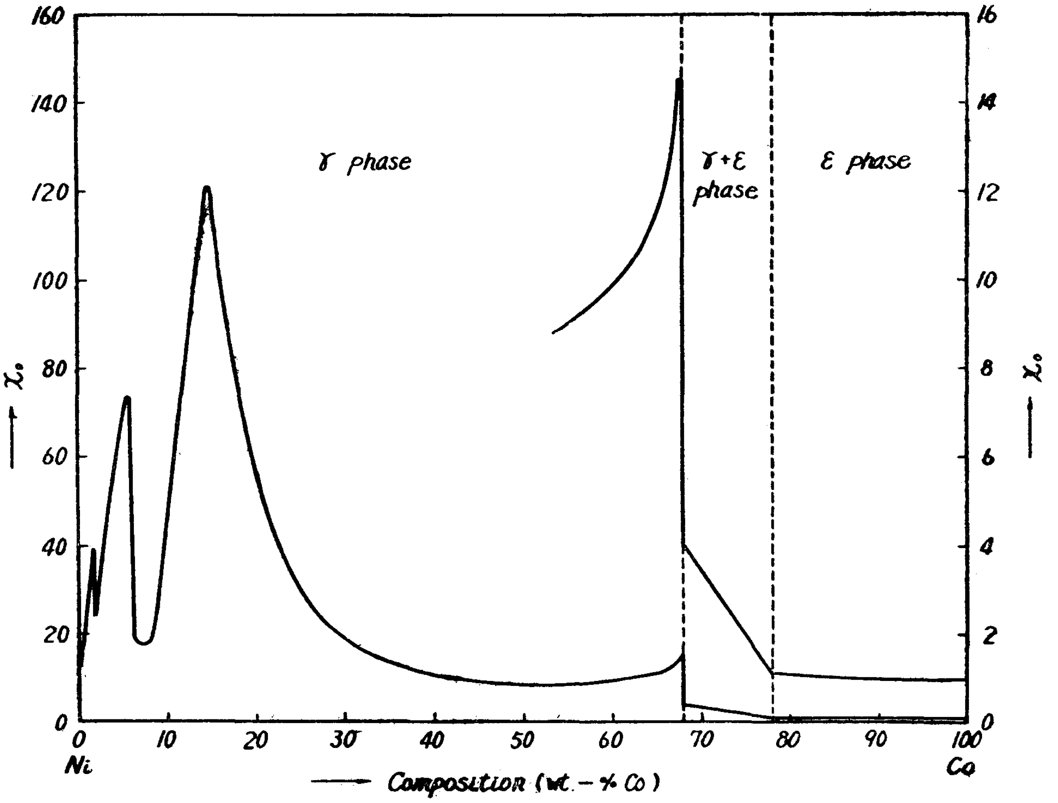

Fig. 7. Initial susceptibility, χ_0, as a function of the composition in nickel-cobalt alloys (after Yamamoto(2)). Two vertical dotted lines mark the phase boundaries.

Summary

The magnetic hysteresis loops have been determined ballistically on annealed nickel-cobalt alloys covering the whole composition range, and their shape, remanence (I_R) and coercive force (H_C) have been studied. Generally, the hysteresis loops of γ-phase (face-centered cubic) alloys are narrow (low H_C) and steep (high I_R), those of ε-phase (close-packed hexagonal) alloys are wide (high H_C) and flat (low I_R), and those of $\gamma+\varepsilon$-phase alloys are intermediate between the two former.

Among γ-phase alloys, alloys containing more than about 25 percent cobalt show abnormal hysteresis loops of the so-called "constricted form". It has been shown that this fact may be explained by the stabilization of domain walls due to the appearence of an additional uniaxial anisotropy along the directions of magnetization vectors during annealing, as a consequence of the interplay between the spin-orbit interaction and orbital valence.

When the magnetizing field decreases from saturation, the magnetization vectors may rotate towards the direction of easy magnetization nearest to the applied field in a ferromagnetic cubic polycrystal composed of equiaxed grains, if the magnetocrystalline anisotropy energy predominates. Then, I_R/I_S (I_S=saturation magnetization) should be 0.831 or 0.866 according to either the sign of the cubic anisotropy constant, K, is positive or negative, if all of the directions of easy magnetization in each grain are equivalent energitically and the orientations of grains are at random. When the internal mechanical stress or induced uniaxial anisotropy favores one of the directions of easy magnetization, however, I_R/I_S should become $(1/3)\times 0.831$ or $(1/4)\times 0.866$ according to the sign of K. The observed values of I_R/I_S of γ-phase alloys actually lie between these two extreme theoretical values. The two minima located at 5 and 20 percent cobalt in the I_R/I_S vs. composition curve may be explained by the fact that K changes its sign at these composition, and the third, very flat and wide, minimum centered at about 50 percent cobalt may be explained by the above-mentioned stabilization of domain walls.

I_R/I_S of a polycrystal having only one direction of easy magnetization like cobalt should be 0.5, but the observed values for ε-phase alloys are only 0.09. These very low observed I_R/I_S values for ε-phase alloys seem to suggest that I_R/I_S may be influenced by the presence of free magnetic poles at grain boundaries.

H_C may eventually be determined by the maximum value of the change in wall energy with position of the wall, and the composition-dependence of H_C in γ-phase alloys containing less than about 20 percent cobalt, may be explained by the change in K with composition. On the other hand, H_C of γ-phase alloys containing more than about 25 percent cobalt may be explained by the above-mentioned stabilization of domain walls, the maximum effect of which may be expected theoretically to occur at 50 percent cobalt. As in I_R/I_S, H_C of ε-phase alloys may be influenced by the presence of free magnetic poles at grain boundaries.