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The ΔE-Effect and Young's Modulus in Nickel-Cobalt Alloys*

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Synopsis

Young's modulus and its change by magnetization (the ΔE-effect) in annealed nickel-cobalt alloys covering the whole composition range have been measured at ordinary temperatures with the method of magnetostrictive vibration. Young's moduli of γ-phase (face-centered cubic) alloys containing less than 20% Co and of two-phase and ε-phase (close-packed hexagonal) alloys containing 69 to 85% Co increase with magnetization throughout (the ΔE-effect of the first kind), while those of γ-phase alloys containing more than 21% Co decrease first at low magnetizations and then increase (the ΔE-effect of the third kind). This negative ΔE-effect at low magnetizations amounts to -5% at 50% Co, being far more conspicuous than those hitherto known. Young's moduli of ε-phase alloys containing more than 85% Co increase at first, but soon decrease, and finally increase again (the ΔE-effect of the second kind).

The saturation value of the ΔE-effect, $(\Delta E/E_0)_s$, shows two conspicuous maxima of 28.0 and 23.7% at 3 and 18% Co, respectively. These values of the ΔE-effect are the highest ones ever found at ordinary temperatures. It is shown that the observed and computed values for $(\Delta E/E_0)_s$ are in good agreement with each other for γ-phase alloys.

Young's modulus at unmagnetized state, E_0, takes a course nearly opposite to that of $(\Delta E/E_0)_s$ in the γ-phase region, showing two minima at 3 and 18% Co. Young's modulus at magnetically saturated state goes parallel to E_0, taking a complicated course even in the γ solid solution range.

I. Introduction

We intended to study systematically Young's modulus and the ΔE-effect in the basic ferromagnetic binary alloys, namely, iron-cobalt, iron-nickel, and nickel-cobalt systems, and the results obtained on the former two alloy systems were previously published(1~3). Among these three alloy systems, we have least information about the nickel-cobalt system; the relation between Young's moduls and the composition had remained unknown and the ΔE-effect had not been measured before the present investigation was made.

The generally accepted phase diagram of nickel-cobalt system(4) shows that at ordinary temperatures the face-centered cubic (γ) phase exists in the composition range from nickel to 70 percent cabalt and the close-packed hexagonal (ε) phase

* The 784th report of the Research Institute for Iron, Steel and Other Metals. The original of this report, written in Japanese language, was previously published in Nippon Kinzoku Gakkai-shi (J. Japan Inst. Metals), **12** (1948), No. 2-3 (p. 4); **B15** (1951), 337.

(1) M. Yamamoto, Phys. Rev., **59** (1941), 768; Nippon Kinzoku Gakkaishi (J. Japan Inst. Metals), **6** (1942), 581.

(2) M. Yamamoto, Nippon Kinzoku Gakkai-shi, **7** (1943), 467.

(3) M. Yamamoto, Nippon Kinzoku Gakkai-shi, **6** (1942), 401.

(4) See, for example, M. Hansen, "*Der Aufbau der Zweistofflegierungen*", Berlin, (1936), p. 498.

exists in the remaining range, the mixture of these two phases occupying only a narrow range of about two percent cobalt. But, our previous measurements of the density(5), magnetic properties(6, 7) and magnetostriction(8) have indicated that the two-phase in this alloy system extended approximately from about 69 to 78 percent cobalt and the present investigation on Young's modulus and ΔE-effect also support this view, as will be shown later.

II. Specimens, method of measurement, and experimental procedure

Specimens employed in the present investigation are slender round bars of nickel-cobalt alloys covering the whole conposition range, which were annealed at 1000°C for 2 hours in a vacuum and used previously by us and their co-workers for the measurements of the density(5), ferromagnetic behavior(6, 7) and longitudinal magnetostriction(8). Specications for the raw materials employed for alloying and the process for preparing the specimens were described previously(5). The composition and length of the specimens are given in Table 1.

Young's modulus and the ΔE-effect have been measured with the method of magnetostrictive vibration. Details of the apparatus used were described in previous papers(9~11). It is to be noted, however, that, in order to raise the sensibility of the apparatus for the measurement of small ΔE-effect in two-phase and ε-phase alloys, UZ-6C6's were used instead of UX-240's as vacuum tubes in the first two stages of the three-stage amplifier in the detecting parts, with which the resonance of the magnetostrictive oscillation of a specimen rod was detected. A water-jacketed magnetizing coil, 40 cm long, of the coil constant of 61.5 Oe/Amp was used for the majority of γ-phase alloys, and another similar coil, 50 cm long, of the coil constant of 58.4 Oe/Amp for the remaining alloys. The homogeneity within one percent of magnetic field produced by the former and latter coils extends over the length of 18 cm and 20 cm in the central portion, respectively, and the highest magnetic fields produced are about 900 and 750 oersteds, respectively.

The experimental procedure is the same as in our previous investigations. The effective magnetic field, which will be simply called magnetic field in the following, was determined by using the data of the magnetization curves for the same specimen

(5) M. Yamamoto, Nippon Kinzoku Gakkai-shi, **11** (1947), No. 11–12 (p. 1) ; Sci. Rep. RITU, **A2** (1950), 871.
(6) M. Yamamoto, Nippon Kinzoku Gakkai-shi, **11** (1947), No. 11–12 (p. 3) ; ibid., **13** (1949) No. 6 (p. 15) ; Sci. Rep. RITU, **A4** (1952), 14.
(7) M. Yamamoto, S. Taniguchi and K. Hoshi, Nippon Kinzoku Gakkaishi, **17** (1953), 615 ; Sci. Rep. RITU, **A6** (1954), 539.
(8) M. Yamamoto and R. Miyasawa, Nippon Kinzoku Gakkai-shi, **B15** (1951), 505 ; Sci. Rep. RITU, **A5** (1953), 22.
(9) M. Yamamoto, Sci. Rep. Tôhoku Univ., **27** (1938), 115 ; Nippon Kinzoku Gakkai-shi, **2** (1938), 495.
(10) M. Yamamoto, Nippon Kinzoku Gakkai-shi, **5** (1941), 167 ; Sci. Rep. Tôhoku Univ., **31** (1943), 101.
(11) M. Yamamoto, Nippon Kinzoku Gakkai-shi, **6** (1942), 331 ; Sci. Rep. RITU, **A3** (1951), 308.

Table 1. Composition, length, density, initial magnetic susceptibility (χ_0), saturation magnetization (I_s), ferromagnetic anisotropy constant (K), and saturation magnetostriction (λ_s) of the nickel-cobalt specimens used, and the measured data of the saturation ΔE-effect ($(\Delta E/E_0)_s$) and of Young's modulus at unmagnetized state (E_0).

No.	Specimen mark	Composition wt.%Co	Length cm	Density(5) g/cm³	χ_0(6)	I_s(6) C.G.S.	$K\times10^{-4}$(6) ergs/cm³	λ_s(8) 10^{-6}	$(\Delta E/E_0)_s$ 10^{-2}	$E_0\times10^{-12}$ dynes/cm²
1	1a	1.0	9.995	8.910	15.2	505	− 3.0	−35.8	12.07	1.945
2	N2a	3.0	10.020	8.920	42.6	525	− 1.8	−35.0	28.04	1.553
3	N2d	3.5	10.010	8.888	46.2	532	− 1.6	−32.8	27.29	1.550
4	NN1a	4.2	10.005	8.926	58	538	− 0.6	−32.5	25.25	1.658
5	NN1b	4.65	”	8.917	50	543	− 1.0	—	21.35	1.754
6	NN2c	5.5	10.000	8.921	72	551	+ 0.8	−33.6	16.84	1.850
7	NN2b	5.9	9.995	8.918	70	557	+ 0.8	−33.5	17.36	1.863
8	SN7a	8.4	10.000	8.884	21.2	582	+ 2.0	−31.5	10.99	2.030
9	2b	11.06	”	8.927	71	610	+ 1.1	−30.3	14.34	1.939
10	N6a	15.20	10.015	8.882	106	647	+ 1.0	−26.8	18.20	1.831
11	N6b	”	10.020	8.846	140	648	+ 1.3	−26.1	18.89	1.820
12	SN8c	18.3	10.005	8.909	74.3	683	+ 0.8	−25.3	23.72	1.775
13	SN6a	20.45	”	8.907	60.5	706	− 0.7	−21.7	15.50	1.905
14	3a	21.0	”	8.870	62.8	711	− 1.0	−22.5	12.55	1.975
15	N7a	23.5	”	8.824	36.4	737	− 1.8	−18.7	7.58	2.027
16	N7d	24.5	”	8.851	29.0	749	− 3.7	−19.1	9.72	2.031
17	N7e	26.4	10.000	8.910	26.1	765	− 3.5	”	9.05	2.081
18	4a	31.3	”	8.916	23.3	817	− 3.3	−13.6	5.77	2.151
19	N8d	34.6	10.010	8.862	13.3	850	− 5.3	−12.4	5.28	2.167
20	5a	40.60	10.005	8.896	13.6	903	− 5.4	− 6.5	5.33	2.140
21	6b	44.5	10.010	8.886	10.5	939	− 6.6	− 7.5	5.96	2.155
22	6a	45.17	10.005	8.895	9.1	946	− 6.9	− 4.8	5.74	2.137
23	7a	49.56	”	8.886	8.3	983	− 9.1	− 0.8	5.57	2.126
24	N9a	55.8	10.010	8.860	9.2	1042	−14.5	3.3	5.33	2.118
25	SN5d	58.1	10.000	8.849	9.8	1062	−13.2	4.9	6.74	2.100
26	8a	59.1	”	8.848	9.1	1071	−15.2	5.5	6.15	2.050
27	SN4a	63.0	9.505	8.888	11.1	1108	−17.8	—	7.01	2.104
28	SN1c	65.8	7.710	8.814	11.8	1129	−15.2	5.5	6.90	2.084
29	SN1b	67.5	10.000	8.844	14.2	1148	−16.0	8.1	7.27	2.086
30	9a	68.95	9.995	8.650	3.92	1158*	—	—	3.63**	1.947
31	10b	75.09	10.010	8.722	1.88	1213*	—	—	3.29**	2.050
32	11a	80.04	9.995	8.836	1.38	1257*	—	—	0.689**	2.108
33	12b	85.01	7.000	8.891	1.03	1301*	—	—	0.316**	2.106
34	13b	90.01	9.995	8.860	1.11	1346*	—	—	0.208**	2.099
35	13c	”	8.615	8.876	1.04	” *	—	—	0.226**	2.110
36	NN15b	92.70	11.795	8.848	1.29	1370*	—	—	0.356**	2.118
37	14b	94.80	9.005	8.858	1.01	1389*	—	—	0.306**	2.100
38	15c	99.86	9.990	8.844	1.94	1434*	—	—	0.432**	2.071

* Determined by an experimental formula(6) $I_s = 542+8.93C$, for $C \geq 34.6$, where C is the cobalt content in weight percent.

** Determined by the extrapolation of a linear part of the $\Delta E/E_0$ *vs.* I/I_s curve to $I/I_s=1$.

as obtained ballistically by one of us(6). Values of densities adopted are those previously obtained by one of us(5) on the same specimens with the 'weighing-in-water' method.

All the measurements were carried out at ordinary temperatures.

III. Experimental results and considerations

From the theoretical point of view, the saturation value of the ΔE-effect must be always positive (or zero), and this conclusion has been verified by experiments. But, although the saturation value is always positive (or zero), it may not always

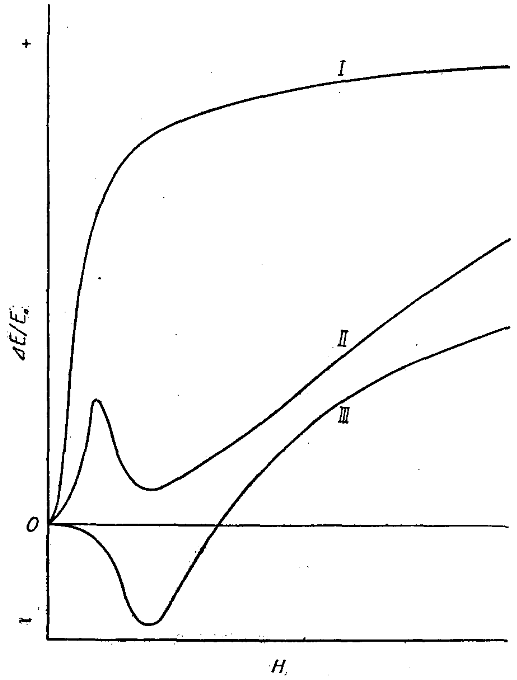

Fig. 1. Schematic representation of the three types of the ΔE-effect (the $\Delta E/E_0$ *vs.* H curves) for low and moderate fields.

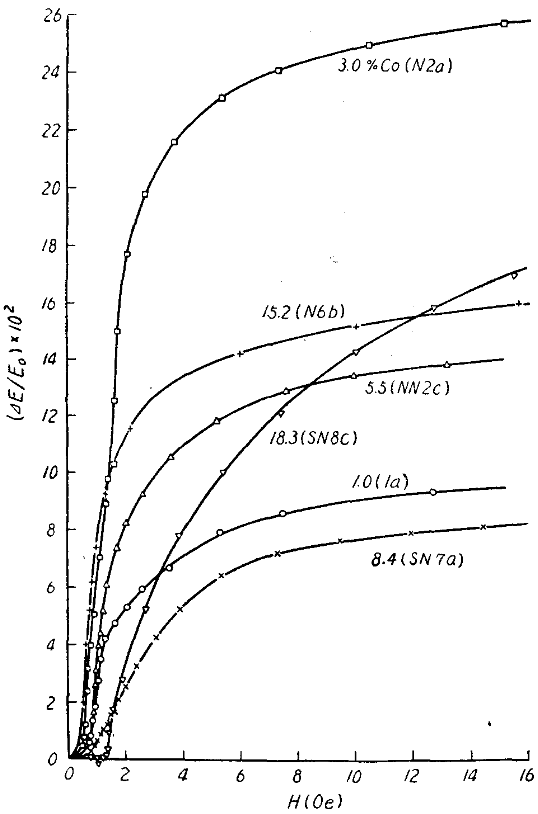

Fig. 2 (a). The ΔE-effect at low fields in γ-phase nickel-cobalt alloys containing less than 20 percent cobalt.

be said that the ΔE-effect is always positive for any intensity of magnetization (or, the ΔE-effect increases monotoneously with magnetization). In fact, according to the experimental results on the ΔE-effect of various polycrystalline ferromagnetic metals and alloys, there are three types of ΔE-effect (Fig. 1). In the first type such as found in nickel, Young's modulus always increases up to saturation with increasing applied magnetic field or with magnetization (the ΔE-effect is positive throughont).[2,9,10,12] In the second type, such as observed in cobalt, Young's modulus increases in the beginning, then decreases, and finally increases again (the ΔE-effect is positive both in the beginning and in the end but it may be positive or negative in the way).[1,10] And, in the third type such as found frequently in alloys, Young's modulus decreases in the beginning, but then increases up to saturation (the ΔE-effect is negative in the beginning, but eventually changes to positive[1,2,12]).

(1) *The ΔE-effect as a function of the magnetic field*

(a) γ-phase alloys (0∼68 %Co)

The ΔE-effects of γ-phase alloys containing less than 20 percent cobalt belong to the first type and those of the remaining γ-phase alloys to the third type. Typical $\Delta E/E_0$-H curves for low fields of γ-phase alloys are shown in Figs. 2(a) and 2(b). The ΔE-effects of alloys containing from 18 to 20 percent cobalt are intermediats between the first and third types; their Young's moduli remain unchanged until the field reaches to about one oersted, and then increase rapidly, as seen from Fig. 2(a).

The composition-dependence of the absolute velue of the negative minimum of

(12) M. Yamamoto, Nippon Kinzoku Gakkai-shi, **6** (1942), 249; Sci. Rep. RITU, **A6** (1954), 446.

the ΔE-effect, $(\Delta E/E_0)_-$, in γ-phase alloys containing more than 21 percent cobalt is given in Fig. 3(a). As seen from the figure, $(\Delta E/E_0)_-$ increases linearly with cobalt content in the beginning, attains a conspicuous high value at 50 percent cobalt and then decreases linearly with cobalt content up to the boundary between the γ-phase and $\gamma+\varepsilon$-phase regions. The negative ΔE-effect appearing at low fields has been observed in iron,[1,13] nickel-copper[12], iron-cobalt[1], iron-nickel[2,14,15] iron-nickel-cobalt[15] and iron-aluminium alloys[13], but it is far more conspicuous in nickel-cobalt alloys[16]. Indeed, it is to be noted that $(\Delta E/E_0)_-$ is of the same order of magnitude as the saturation values of ΔE-effect, $(\Delta E/E_0)_s$, as will be shown later. Parallel to this change of $(\Delta E/E_0)_-$ with composition, the magnetic field where $(\Delta E/E_0)_-$ locates, H_-, rises with increasing cobalt content in the beginning, but lowers again from 50 percent cobalt,

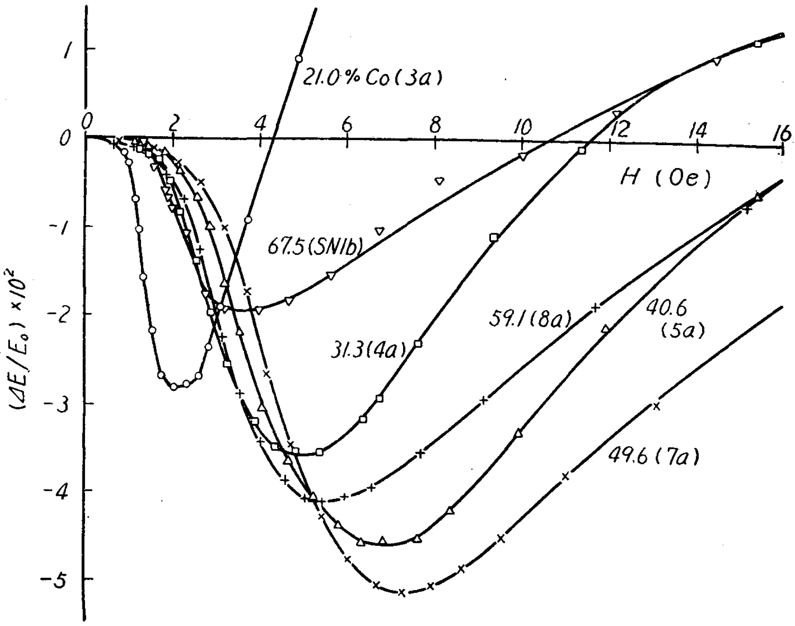

Fig. 2 (b). The ΔE-effect at low fields in γ-phase nickel-cobalt alloys containing more than 20 percent cobalt.

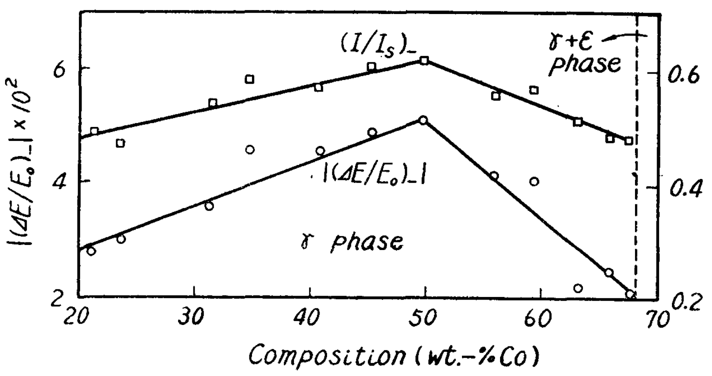

Fig. 3 (a). $(\Delta E/E_0)_-$ and $(I/I_s)_-$ as functions of the composition in γ-phase nickel-cobalt alloys containing more than 20 per cent cobalt.

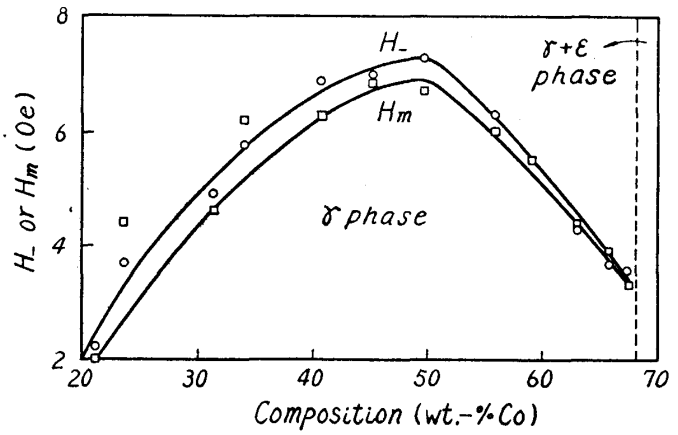

Fig. 3 (b). H_- and H_m as dependent on the composition in γ-phase nickel-cobalt alloys containing more than 20 percent cobalt.

(13) M. Yamamoto and S. Taniguchi, Nippon Kinzoku Gakkai-shi, (1954), 584.
(14) H.J. Williams, R.M. Bozorth, and H. Christensen, Phys. Rev., 59 (1941), 1005 (68 permalloy).
(15) N. Kunitomi, J. Phys. Soc. Japan, 8 (1953), 26 (65 permalloy and a perminvar).
(16) The highest value of $(\Delta E/E_0)_-$ so far obtained is 2.1 percent for an iron-cobalt alloy containing 70 percent cobalt. See reference (1).

as shown in Fig. 3(b), H_- is nearly the same as the magnetic field where the magnetic suceptibility is maximum, H_m, but generally H_- is a little higher than H_m (Fig. 3(b)). The negative ΔE-effect at low fields will be discussed in a separate paper.

Typical $\Delta E/E_0$-H curves for high fields are shown in Figs. 4(a) and 4(b). As already found[9, 12, 2], the ΔE-effect of nickel (containing 0.6 percent cobalt) shows a secondary increase at intermediate fields. This phenomenon is no longer observed with an alloy containing 3.0 percent cobalt, but appears again in alloys containing more than 20 percent cobalt. One of the authors[10, 12] has discussed this secondary increase of the ΔE-effect in relation to the ferromagnetic anisotropy energy and concluded that, as the absolute magnitude of the ferromagnetic anisotropy constant, $|K|$, becomes smaller, it should occur at more and more low fields and over a more and more narrow field range and finally it mingles into the primary rapid increase at low fields. As already known[17], $|K|$ is comparatively small for nickel, decreases with an addition of cobalt, and becomes zero at 5 percent cobalt. The positive, but small, value of K continues up to 19.5 percent cobalt. After the return to negative again, $|K|$ increases more and more rapidly. Actually, the secondary increase of the ΔE-effect could not be recognized with alloys containing less than 20 percent cobalt

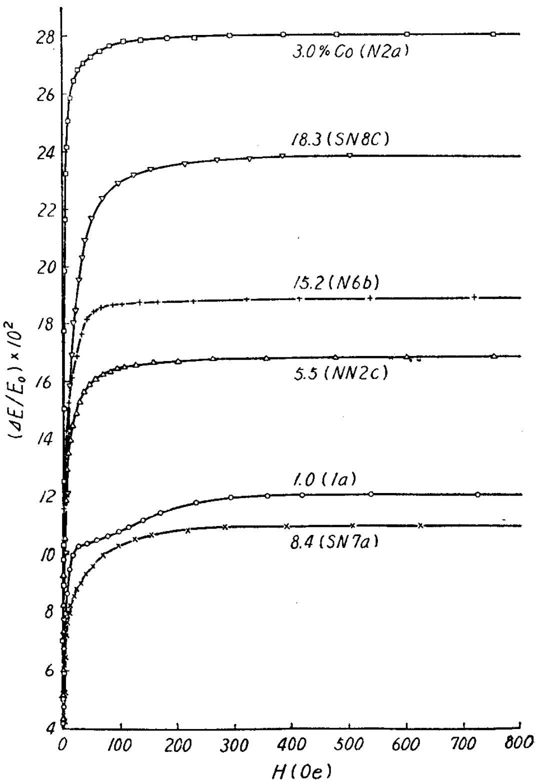

Fig. 4 (a). The ΔE-effect in γ-phase nickel cobalt alloys containing less than 20 percent cobalt.

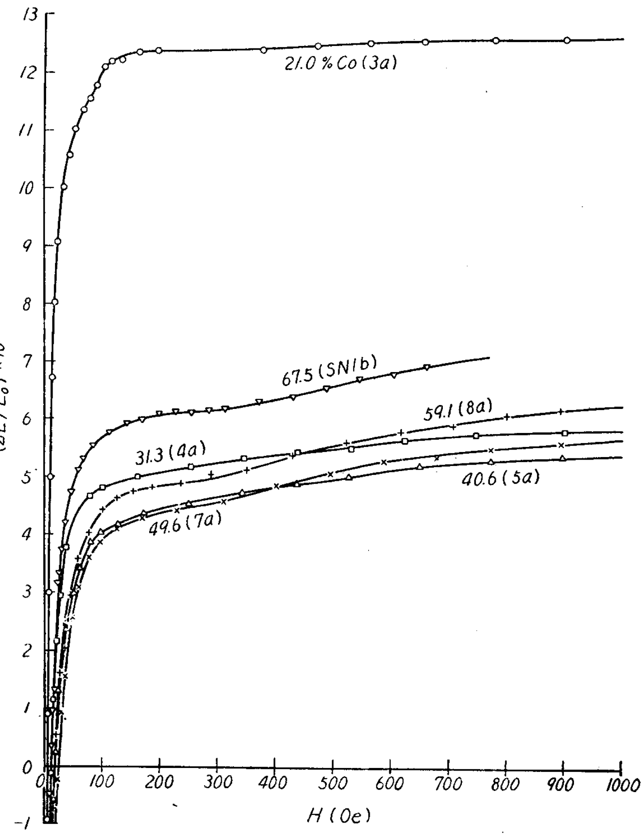

Fig. 4 (b). The ΔE-effect in γ-phase nickel-cobalt alloys containing more than 20 percent cobalt.

(17) J. W. Shih, Phys. Rev., **50** (1936), 376; L. W. McKeeham, Phys. Rev., **51** (1937), 136; M. Yamamoto, reference (6).

except nickel, but it appears again in alloys containing more than 21 percent cobalt and over a more and more wide field range as the cobalt content increases. It is to be noted, further, that, corresponding to the said composition-dependence of K, at fields lower than 900 oersteds the ΔE-effects of alloys containing less than 40 percent cobalt saturate, but those of alloys containing more than 45 percent cobalt do not yet saturate, being more and more difficult to saturate as the cobalt content increases.

(b) $\gamma+\varepsilon$-phase (69~78 % Co) and ε-phase (78~100 %Co) alloys.

When the cobalt content† increases over 68 percent cobalt, the type of the $\Delta E/E_0$-H curve suddenly changes from the thrid to the first type again, and it remains unchanged in the $\gamma+\varepsilon$-phase region and also in the first several percent-cobalt range of the ε-phase region (Fig. 5). Then, it changes into the second type over 85 percent cobalt (Fig. 6). In ε-phase alloys containing 90~95 percent cobalt, in particular, the temporaly decrease of their Young's moduli at intermediate fields, occurs over a very

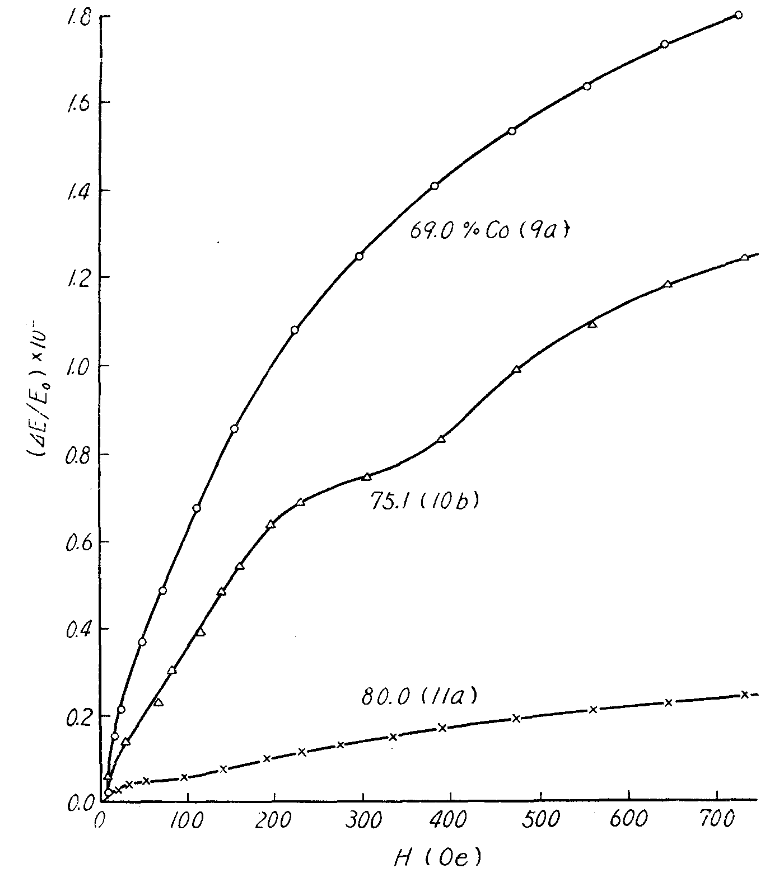

Fig. 5. The ΔE-effect in $\gamma+\varepsilon$-phase nickel-cobalt alloys. The curve for a 80% Co alloy belonging to the ε-phase region is also shown for comparison.

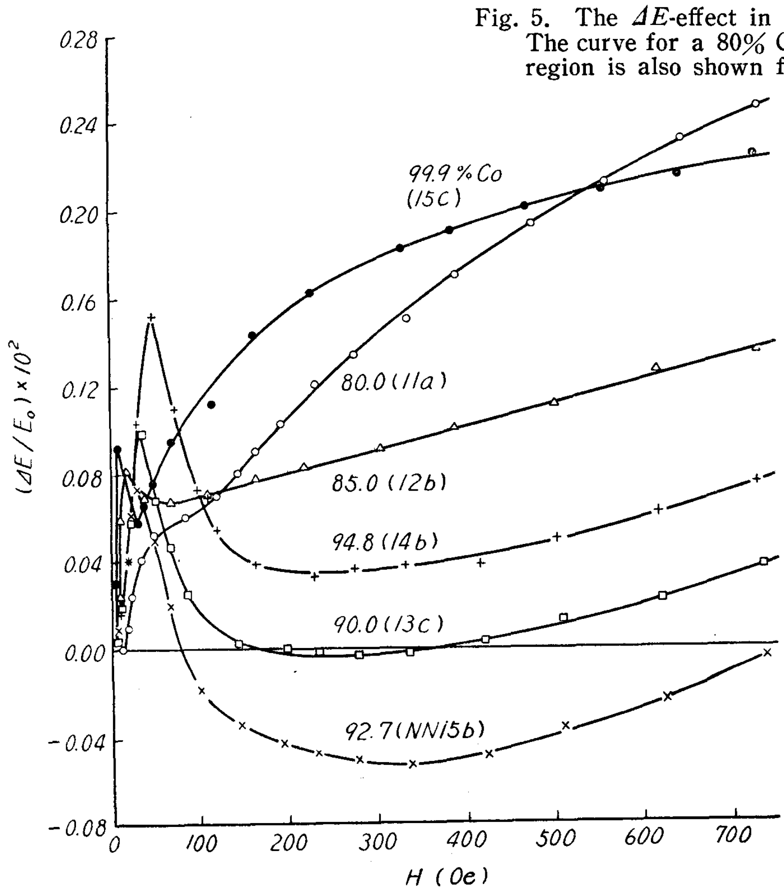

Fig. 6. The ΔE-effect in ε-phase nickel-cobalt alloys.

wide field range and may become negative. As seen from Figs. 5 and 6, the ΔE-effects of $\gamma+\varepsilon$-phase and ε-phase alloys are far from saturation at the maximum measuring field (about 750 Oe). Further, as seen evidently in Fig. 6, the $\Delta E/E_0$-H curve of 80 percent cobalt alloy shows a decrease in ascending rate at about 100 oersteds, and this seems to indicate a transition from the first to the second type of the ΔE-effect. If so, the ΔE-effect of the second type may be characteristic to the magnetically uniaxial hexagonal metal polycrystals.

The maximum and minimum values of the ΔE-effect of the second type, in general, decrease wsth increasing cobalt content, but increase again after the cobalt content exceeds about 90 percent cobalt, while the fields where these maximum and minium values locate, H_{max} and H_{min}, take a course entirely inverse to the above-stated, and goes parallel with the field where the magnetic susceptibility becomes maximum.

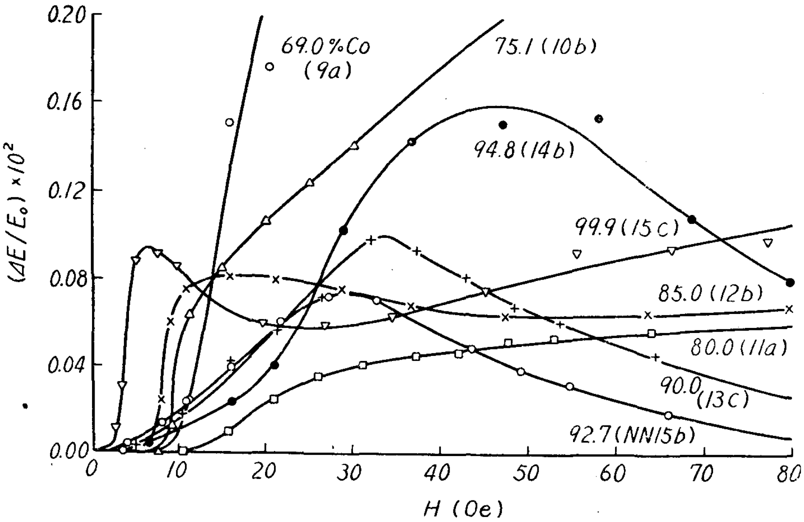

Fig. 7. The ΔE-effect at low fields in $\gamma+\varepsilon$-phase and ε-phase nickel-cobalt alloys.

The $\Delta E/E_0$-H curves of $\gamma+\varepsilon$-phase and ε-phase alloys at low fields (0~100 Oe) are shown in Fig. 7, which indicates that their Young's moduli do not change until the field attains several oersteds.

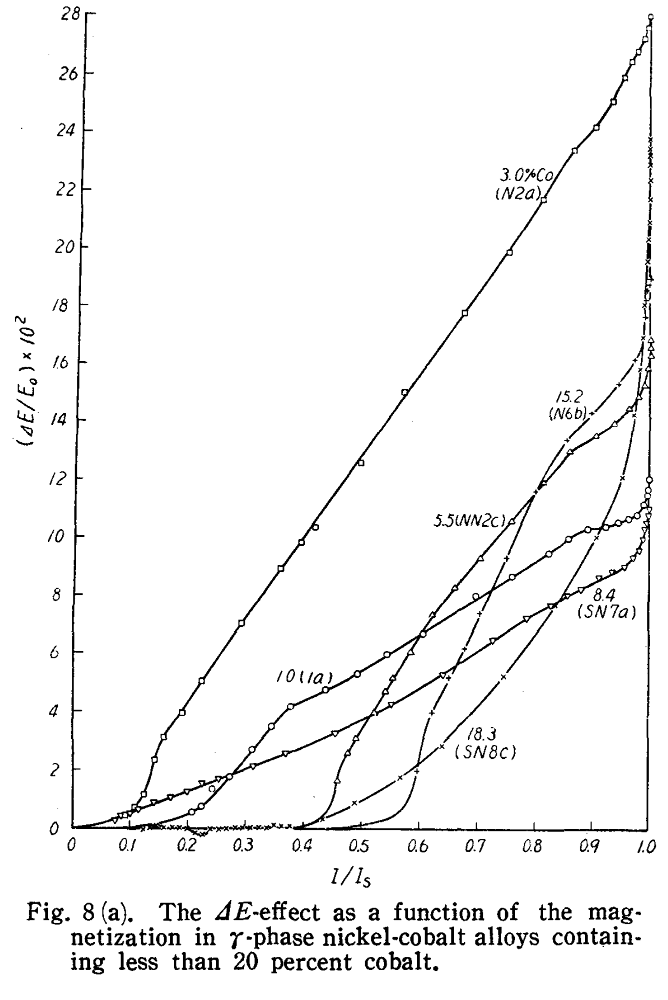

Fig. 8 (a). The ΔE-effect as a function of the magnetization in γ-phase nickel-cobalt alloys containing less than 20 percent cobalt.

(2) *The ΔE-effect as a function of the intensity of magnetization*

The relations between $\Delta E/E_0$ and the reduced magnetization, I/I_s (I_s = saturation magnetization), in γ-phase alloys are shown in Figs. 8(a) and 8(b). The curves of alloys containing more than

20 percent cobalt show, corresponding to the above-mentioned negative ΔE-effects at low fields, conspicuous negative minima in a wide magnetization range. The relation between the reduced magnetization where these minimum values locate, $(I/I_s)_-$ and composition is similar to that between $|(\Delta E/E_0)_-|$ and composition, as shown in Fig. 3(a).

$\Delta E/E_0$-I/I_s curves of $\gamma+\varepsilon$-phase and ε-phase alloys are shown in Figs. 9 and 10, respectively. Corresponding to the above-mentioned course of $\Delta E/E_0$-H curves (Fig. 6), $\Delta E/E_0$-I/I_s curves of ε-phase alloys containing more than 85 percent cobalt show conspicuous maxima and minima. The relations be- †

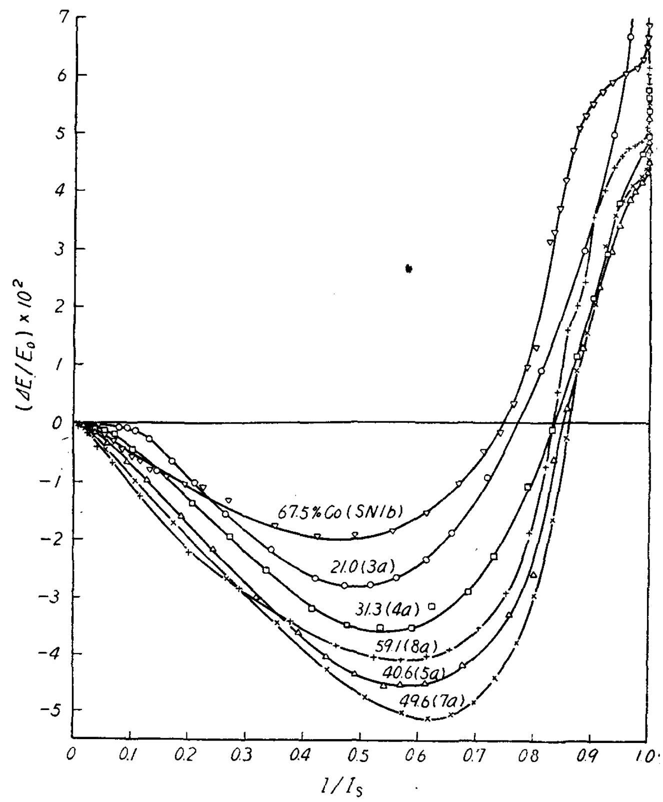

Fig. 8 (b). The ΔE-effect as a function of the magnetization in γ-phase nickel-cobalt alloys containing more than 20 percent cobalt.

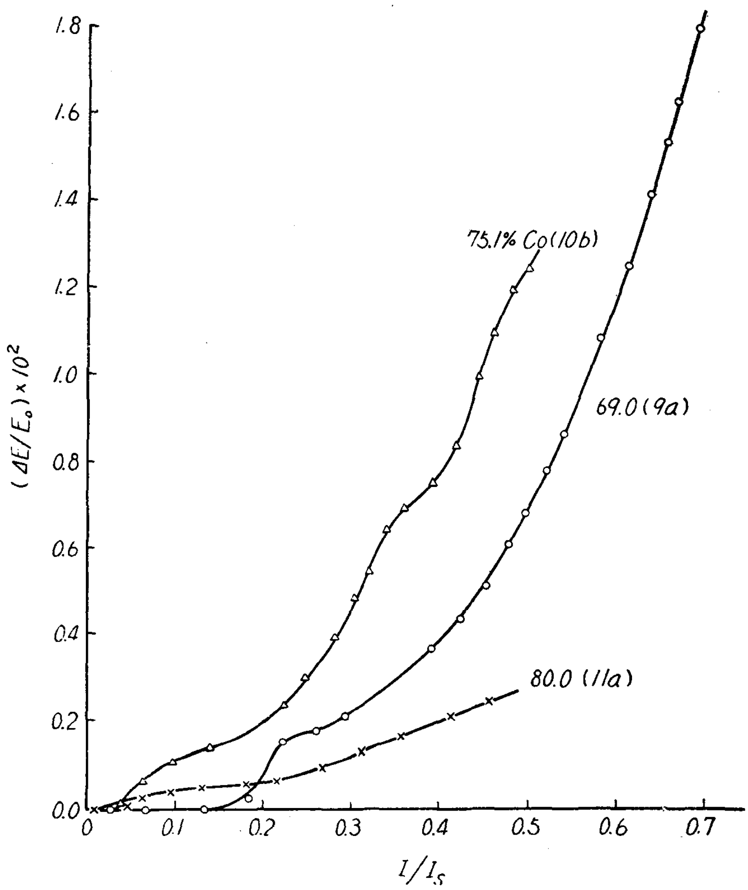

Fig. 9. The ΔE-effect as a function of the magnetization in $\gamma+\varepsilon$-phase nickel-cobalt alloys. The curve for a 80% Co alloy belonging to the ε-phase region is also shown for comparison.

† tween the reduced magnetizations where the maximum and minimum values locate and composition is similar to those between H_{max} as well as H_{min} and composition mentioned before.

(3) *The value of the ΔE-effect for the highest measuring field as a function of the composition*

The relation between the value of the ΔE-effect at the highest measuring field, $(\Delta E/E_0)_{max}$, and composition is shown in Fig. 11. The highest measuring field are 900 oersteds for the majority of γ-phase alloys and 750

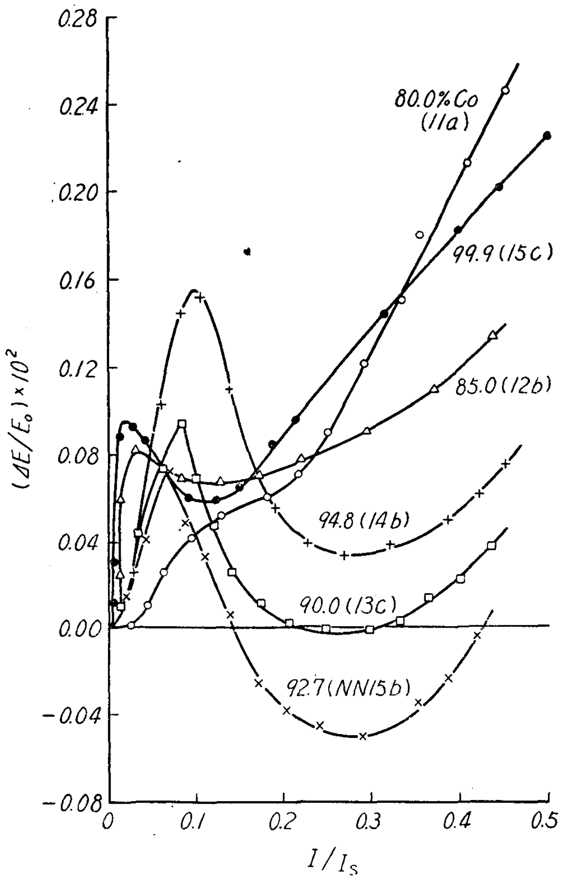

Fig. 10. The ΔE-effect as a function of the magnetization in ε-phase nickel-cobalt alloys.

oersteds for the remaining alloys. It may be seen from Fig. 4(b) that the ΔE-effects of γ-phase alloys containing more than 45 percent cobalt do not completely but nearly saturate at these highest measuring fields. Accordingly, for γ-phase alloys, $(\Delta E/E_0)_{max}$ may be regarded as the saturation value, $(\Delta E/E_0)_s$, without an appreciable error. But, for $\gamma+\varepsilon$-phase and ε-phase alloys, $(\Delta E/E_0)_{max}$ is far from $(\Delta E/E_0)_s$, as may be seen from Figs. 5 and 6.

As is well known, $(\Delta E/E_0)_s$ for nickel (12.07 percent for 1.0 percent cobalt) is far greater than those for iron and cobalt. By adding a small quantity of cobalt to nickel, $(\Delta E/E_0)_s$ increases very considerably and amounts to 28.04 percent at 3.0 percent cobalt. With a further increase of cobalt content, $(\Delta E/E_0)_s$ decreases rapidly to nearly the same magnitude as that of nickel, but soon recovers again and reaches to the second

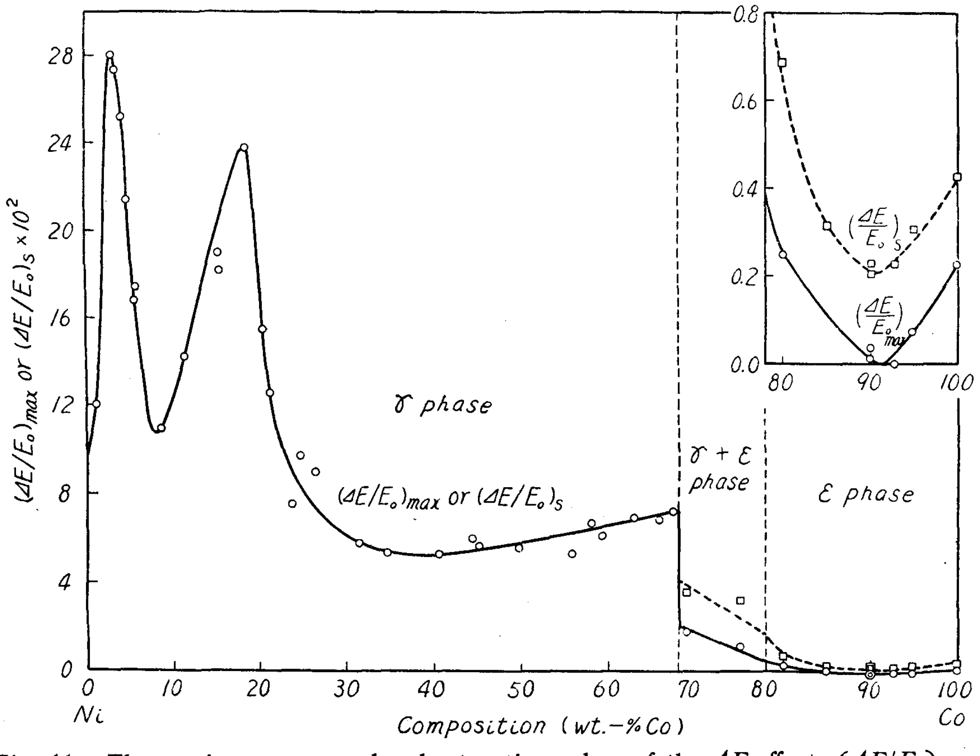

Fig. 11. The maximum measured and saturation values of the ΔE-effect, $(\Delta E/E_0)_{max}$ and $(\Delta E/E_0)_s$ as dependent on the composition in nickel-cobalt alloys. For γ-phase alloys, $(\Delta E/E_0)_{max}$ is practically equal to $(\Delta E/E_0)_s$.

maximum (23.72 percent) at 18.3 percent cobalt. These two maximum values are higher than the highest value of ΔE-effect so far observed at ordinary temperatures, namely, 22.1 percent for an iron-cobalt alloy containing 50 percent cobalt as obtained by one of us(1). Then, $(\Delta E/E_0)_s$ decreases rapidly and then slowly, and after reaching to a flat minium of about 5 percent at 35~40 percent cobalt, it increases slowly up to the boundary between the γ-phase and $\gamma+\varepsilon$-phase regions.

Since $(\Delta E/E_0)_{max}$ of a γ-phase alloy containing 67.5 percent cobalt nearest to this phase boundary, is 7.3 percent and that of a $\gamma+\varepsilon$-phase alloy containing 69.0 percent cobalt is 1.8 percent, it follows then that $(\Delta E/E_0)_{max}$ shows a rather discontinuous decrease at this phase boundary. It is to be noted that $(\Delta E/E_0)_{max}$ for 67.5 percent cobalt is practically equal to $(\Delta E/E_0)_s$, but that for 69.0 percent cobalt is consiederably far from $(\Delta E/E_0)_s$. Now, let us extrapolate the $\Delta E/E_0$-I/I_s curve of 69.0 percent cobalt alloy (Fig. 9) to $I/I_s=1.0$ assuming this curve to be linear between $I/I_s = 0.7$ and 1.0, then the value of $(\Delta E/E_0)_s$ thus obtained is only 3.6 percent. It may, then, be concluded that $(\Delta E/E_0)_s$ also decreases discontinuously at this phase boundary. As will be mentioned later, the absolute magnitude of Young's modulus also decreases abruptly at this phase boundary. The abrupt changes in the density(5), magnetic properties(6,7) and magnetostriction effect(8) at this phase boundary were reported previously by the present authors and their collaboraters. These abrupt changes may be due to the influcence of the volume change accompanied by the $\gamma\rightarrow\varepsilon$ transformation and of the uniaxial ferromagnetic properties of the transformed ε-phase, as suggested previously(7).

In the $\gamma+\varepsilon$-phase region, both $(\Delta E/E_0)_{max}$ as well as $(\Delta E/E_0)_s$ as determined by extrapolation of the $\Delta E/E_0$-I/I_s curves diminish with increasing cobalt content and at the boundary between the $\gamma+\varepsilon$-phase and ε-phase regions they reach to the order of one precent and two percent, respctively (Fig. 11). In the ε-phase region, they decrease in the beginning, but after reaching minima (0 percent for $(\Delta E/E_0)_{max}$ and 0.2 percent for $(\Delta E/E_0)_s$, respectively) at about 90 percent cobalt, increase slowly up to cobalt. $(\Delta E/E_0)_{max}$ and $(\Delta E/E_0)_s$ for cobalt are 0.22 percent and 0.4 percent, respectively.

Comparison with theory as regards the saturation values of the ΔE-effect in γ-phase alloys. Previously one of the authors indicated that for polycrystalline nickel-copper(12), iron-cobalt(1), and iron-nickel(2) alloys, the observed values of the saturation ΔE-effect were in good agreement with the values calculated from a semi-empirical formula :

$$\left(\frac{\Delta E}{E_0}\right)_s = 0.7\cdot\frac{\chi_0\lambda_s^2E_0}{I_s^2}\Big/\left(1-0.7\cdot\frac{\chi_0\lambda_s^2E_0}{I_s^2}\right), \qquad (1)$$

where χ_0, λ_s, and E_0 are the initial susceptibility, saturation magnetostriction, and Young's modulus at unmagnetized state, respectively. As shown in Fig. 12, values of $(\Delta E/E_0)_s$ as computed from Eq. (1) by using the values for χ_0(6), I_s(6), λ_s(8), and E_0 as measured on the same specimens as employed for the ΔE-effect measurements and given in Table 1 —the curve denoted as "calculated, I"— agree qualitatively well with the measured values, but in the high-cobalt composition range they are

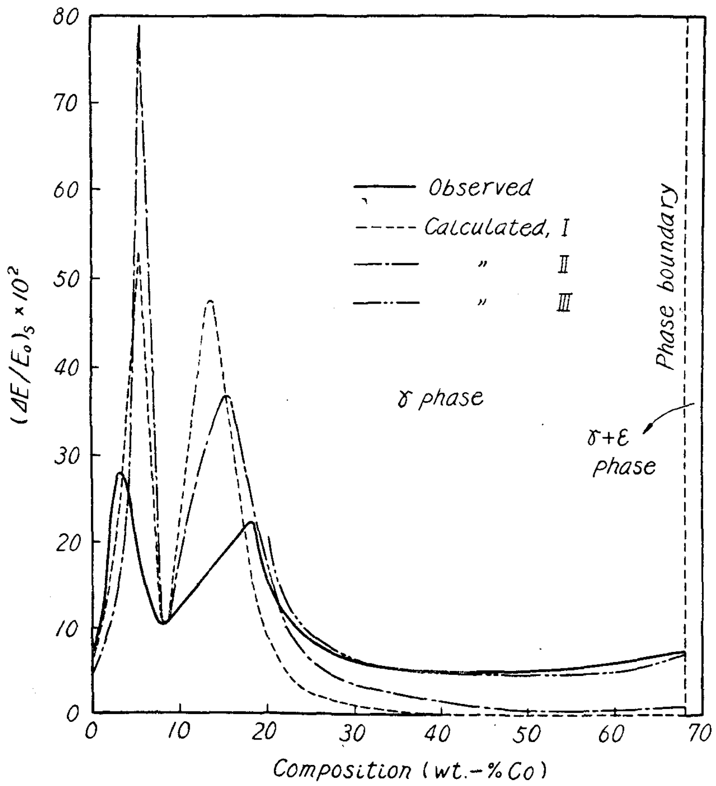

Fig. 12. Comparison between the measured data and some theoretical data as regard to the saturation ΔE-effect in γ-phase nickel-cobalt alloys.

too small.

Now, theoretically Eq. (1) is an approximate formula obtained by averaging with Reuss' method only the contributions from the displacements of non−180° domain walls in the case where the magnetocrystaline anisotropy energy predominates over the magnetic strain energy(18). So, λ_s in Eq. (1) is really to be the saturation magnetostriction in the direction of easy magnetization, λ_e, and λ_e is equal to λ_s only if the magnetostriction is isotropic. However, one of the authors (Yamamoto) and Miyasawa(19) have recently shown that for γ-phase nickel-cobalt alloys the magnetostrictive constants λ_{111} and λ_{100} as function of the composition C (in weight percent cobalt) may be expressed by

$$\lambda_{111}=(-30+0.09C)\times 10^{-6} \quad \text{and} \quad \lambda_{100}=(-49+1.96C)\times 10^{-6}, \qquad (2)$$

namely, the magnetostriction of an alloy containing about 10 percent cobalt is isotropic and the anisotropy of magnetostriction in a 25 percent cobalt alloy is nearly the same as that of nickel, but as the cobalt content increases over 25 percent cobalt the saturation magnetostriction along the directions of easy and difficult magnetization [111] and [100] have the sign different to each other and its anisotropy increases more and more. Accordingly, we have computed $(\Delta E/E_0)_s$ using, instead of λ_s, values for λ_e as determined from Eq. (2) and obtained values —"calculated, II"—, which agree better than "calculated, I" with, but are still too lower than, the measured data in the high-cobalt composition range, as seen from Fig. 12.

It is natural to suppose that such difference between the measured and computed data of the saturation ΔE-Effect for high-cobalt γ-phase nickel-kobalt alloys may be due to the neglect of the contribution from the rotation of magnetization vectors in the above calculations. The total saturation ΔE-effect is generally given by

$$\left(\frac{\Delta E}{E_0}\right)_s = E_0\left\{\left(\frac{de_m}{dF}\right)_0^{(W)} + \left(\frac{de_m}{dF}\right)_0^{(R)}\right\} \Big/ \left[1 - E_0\left\{\left(\frac{de_m}{dF}\right)_0^{(W)} + \left(\frac{de_m}{dF}\right)_0^{(R)}\right\}\right], \qquad (3)$$

(18) See M. Yamamoto, reference (12).

(19) M. Yamamoto and R. Miyasawa, Nippon Kinzoku Gakkai-shi, B **15** (1951), 509; Sci. Rep. RITU, **A5** (1953), 113.

where $(de_m)_0$ is the change of the magnetostrictive strain caused by the application of the small external stress, dF, at the unmagnetized state, and (W) and (R) indicate the contributions to $(de_m)_0$ from the domain wall displacements and from the rotation of magnetization vectors caused by dF, respectively. For cubic metal and alloy polycrystals, $(de_m)_0^{(W)}$ as obtained by the Reuss' method of average is given by

$$(de_m)_0^{(W)}=C(\chi_0\lambda_e^2/I_s^2)dF \ , \qquad (4)$$

where C is 3/5 according to the statistical domain theory[20] and 4/5 accoding to the orthodox domain theory[21] (the numerical factor 0.7 in Eq. (1) is the average of these two values). It is to be noted that χ_0 in Eq. (4) which is the same as χ_0 in Eq. (1) is the (isotropic) initial susceptibility contributed only from the non-180° wall displacements, while the experimentally determined initial susceptibility is the sum of contributions from the 180° and non-180° wall displacements. On the other hand, $(de_m)_0^{(R)}$ is given by :[22]

$$(de_m)_0^{(R)}=(3/5)\lambda_{111}^2 dF/K \qquad \text{for} \quad K>0 \ , \qquad (5)$$

and

$$(de_m)_0^{(R)}=(3/5)\{\lambda_{100}^2+(\lambda_{111}^2)/2\}dF/(-K) \qquad \text{for} \quad K<0 \ . \qquad (6)$$

It is to be noted that all of Eqs. (4), (5) and (6) are derived under the assumption that the domain distribution is uniform at unmagnetized state, which may really not be probable. The values of $(\Delta E/E_0)_s$ as computed from Eqs. (3), (4) and (5) or (6) using the values for K[6] as measured on the same specimens—the curve denoted as "calculated, III"— agree very well with the measured data in the high-cobalt composition range, as seen from Fig. 12.

(4) *Young's moduli at unmagnetized and at magnetically saturated states as functions of the composition*

The relation between Young's modulus at unmagnetized state, E_0, and composition is given in Fig. 13. The E_0 vs. composition curve in the γ-phase region shows a rather unexpected complexity and takes a course nearly opposite to that of $(\Delta E/E_0)_s$. E_0 of nickel (2.0×10^{12} dynes/cm^2) decreases rapidly by the addition of a small cobalt content to 1.55×10^{12} dynes/cm^2 at 3.0~3.5 percent cobalt, but it soon recovers to the same order of magnitude as that of nickel at about 9 percent cobalt. Further, it shows again a minimum locating at 18 percent cobalt and a flat maximum

(20) N. Akulov and E. Kondorsky, **78** (1932), 801; **85** (1933), 661; W.F. Brown, Phys. Rev., **52** (1932), 335; M. Takagi, Sci. Rep. Tôhoku Univ., **28** (1939), 85.

(21) W. Döring, Z. Phys., **114** (1939), 579.

(22) Eqs. (5) and (6) have been obtained by averaging, over randomly oriented crystal grains, of the following expressions for single crystals derived by R. Kimura, Proc. Phys. Math. Soc., **22** (1930), 45 :

$$(de_m)_0^{(R)}=3(\lambda_{111}^2/K)(\beta_1^2\beta_2^2+\beta_2^2\beta_3^2+\beta_1^2\beta_1^2)dF \quad \text{for } K>0$$

and

$$(de_m)_0^{(R)}=(-9/4K)\left\{\lambda_{100}^2(\beta_1^4+\beta_2^4+\beta_3^4-\frac{1}{3})+(2/3)\lambda_{100}^2(\beta_1^2\beta_2^2+\beta_2^2\beta_3^2+\beta_3^2\beta_1^2)dF\right\} \text{for } K<0,$$

where β_1, β_2, and β_3 are the direction cosines of the external stress referred to the crystal axes. It is to be noted that the sign of the second term of Kimura's second equation is misprinted as $-$.

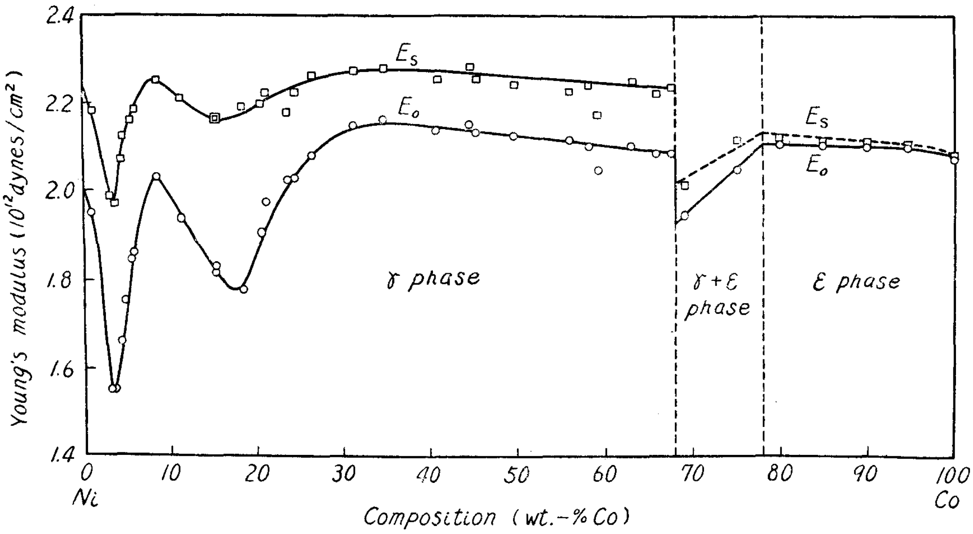

Fig. 13. Young's moduli at unmagnetized and at magnetically saturated states, E_0 and E_s, as functions of the composition in nickel-cobalt alloys.

amounting to 2.15×10^{12} dynes/cm^2 locating at about 35 percent cobalt and then decreases slowly up to the boundary between the γ-phase and $\gamma+\varepsilon$-phase regions.

E_0 decrease abruptly by about 8 percent at this phase boundary, but it recovers in the $\gamma+\varepsilon$-phase region, and then decreases slowly up to cobalt in the ε-phase region. E_0 for cobalt is 2.1×10^{12} dynes/cm^2.

It is a remarkable fact that Young's modulus of nickel decreases by about 20 percent by the addition of only 3~4 percent of cobalt. This fact may indicate that, as one of causes why literature values for Young's modulus of nickel differ considerably from each other, the cobalt content contained as an impurity in the specimen should be taken into considerations in addition to the mecanical and heat treatments offered to the specimen prior to the measurement, the magnetic state of the specimen, and the magnitude and distribution of stress in the specimen during the measurement.

Values of Young's modulus at magnetically saturated state, E_s, computed by the relation $E_s = E_0\{1+(\Delta E/E_0)_s\}$ are also plotted in Fig. 13. E_s lies above E_0 and goes nearly parallel to E_0. It is to be noted that E_s does not take an simple course even in the γ-phase region, in contradiction to an apparently reasonable view that an E_s vs. composition curve should take a simple course in a ferromagnetic solid solution. Similar examples have been furnished by nickel-copper(12), iron-cobalt(1), iron-nickel(2), and iron-aluminium alloys(13). This seems to indicate that the cohesion of ferromagnetic crystals involves a contribution from its ferromagnetism.

Summary

The ΔE-effect and Young's modulus in annealed nickel-cobalt alloys covering the whole composition range has been measured at ordinary temperatures with the method of magnetostrictive vibration.

Young's moduli of γ-phase (face-centered cubic) alloys containing less than 20 percent cobalt and of two-phase and ε-phase (close-packed hexagonal) alloys con-

taining 69 to 85 percent cobalt increase with magnetization throughout (the ΔE-effect of the first kind), while those of remaining γ-phase alloys containing more than 20 percent cobalt decrease at first at low magnetizations and then increase (ΔE-effect of the third kind). This negative ΔE-effect at low magnetaization is of the same order of magnitude as the saturation value of the ΔE-effect, $(\Delta E/E_0)_s$, and amounts to -5 percent at 50 percent cobalt, being far more conspicuous than those hitherto known. Young's moduli of remaining ε-phase alloys containing more than 85 percent cobalt increase at first, but soon decrease, and finally increase again (the ΔE-effect of the second kind).

$(\Delta E/E_0)_s$ shows two conspicuous maxima of 28.0 and 23.7 percent at 3 and 18 percent cobalt, respectively. These values of the ΔE-effect are the highest ones ever found at ordinary temperatures. $(\Delta E/E_0)_s$ is estimated to be only 0.4 percent for cobalt. It has been shown that the observed values of $(\Delta E/E_0)_s$ for low cobalt alloys agree well with values calculated from a formula, derived theoretically under the condition that the ferromagnetic anisotropy energy predominated over the magnetic strain energy, namely

$$\left(\frac{\Delta E}{E_0}\right)_s = 0.7\cdot\frac{\chi_0\lambda_e{}^2E_0}{I_s^2}\Bigg/\left(1-0.7\cdot\frac{\chi_0\lambda_e{}^2E_0}{I_s^2}\right),$$

where χ_0 is the initial susceptibility, λ_e is the saturation magnetostriction along the directions of easy magnetization, E_0 is Young's modulus at unmagnetized state, and I_s the saturation magnetization. While, for high-cobalt γ-phase alloys for which the ferromagnetic anisotropy constant, K, is negative, the observed $(\Delta E/E_0)_s$ value are not consistent with the above formula, but agree well with values calculated from a formula involving the contribution from the rotation of magnetization vectors in addition to the wall displacement contribution, namely:

$$\left(\frac{\Delta E}{E_0}\right)_s = E_0\left\{0.7\times\frac{\chi_0\lambda_{111}^2}{I_s^2}+\frac{3}{5}\cdot\frac{\lambda_{100}^2+(\lambda_{111}^2/2)}{(-K)}\right\}$$
$$\div\left[1-E_0\left\{0.7\times\frac{\chi_0\lambda_{111}^2}{I_s^2}+\frac{3}{5}\cdot\frac{\lambda_{100}^2+(\lambda_{111}^2/2)}{(-K)}\right\}\right],$$

where λ_{100} and λ_{111} are the saturation magnetostriction along the [100] and [111] directions of a single crystal, respctively.

Young's modulus at unmagnetized state takes a course nearly opposite to that of $(\Delta E/E_0)_s$ in the γ-phase region, showing two minima at 3 and 18 percent cobalt. Young's modulus at magnetically saturated state goes parallel to that at unmagnetized state, taking a complicated course even in the γ solid solution range.

It is to be added that both the ΔE-effect and Young's modulus decrease abruptly at the boundary between the γ-phase $\gamma+\varepsilon$-phase regions.

In conclusion, the authors wish to express their heartly thanks to Mr. K. Endô and Mr. T. Shibuya who helped them zealously during the course of the present work. A partial fund required for this work was furnished from the Grant in Aid for the Fundamental Scientific Researches of the Ministry of Education.