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journal or publication title	Science reports of the Research Institutes, Tohoku University. Ser. A, Physics, chemistry and metallurgy
volume	12
page range	291-308
year	1960
URL	http://hdl.handle.net/10097/26985

Young's Modulus and Its Variation with Magnetization in Annealed Iron-Cobalt Alloys*

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(Received April 28, 1960)

Synopsis

With annealed iron-cobalt alloys covering the whole composition range, Young's moduli and their changes with magnetization (the ΔE effect) in magnetic fields up to 900 Oe have been measured at ordinary temperatures using the method of magnetostrictively excited longitudinal vibration. In this connection, the density and some ferromagnetic properties have also been determined.

It has been found that the negative ΔE effect occurs at weak magnetic fields in most alloys excluding 45∼50 and 100 %Co. The absolute magnitude of the negative minimum of the ΔE effect is, at most, of the order of 0.1 % in alloys containing less than 45 %Co, while it amounts to more than 2 % in alloys containing 65∼70 %Co. The maximum measured values of the ΔE effect, $(\Delta E/E_0)_{max}$, which are approximate to the saturation values, $(\Delta E/E_0)_s$ excepting only for pure cobalt, are all positive in the whole composition range of the alloys. The $(\Delta E/E_0)_{max}$ vs. composition curve exhibits a very sharp and high peak of 22.10 % at about 50 %Co. The trend of the curve in the α (body-centered cubic) phase range agrees qualitatively very well and quantitatively fairly well with the results of calculation by a formula

$$(\Delta E/E_0)_s=(0.7\chi_0\lambda_s^2E_0/I_s^2)/(1-0.7\chi_0\lambda_s^2E_0/I_s^2),$$

where χ_0, λ_s, I_s, and E_0 are the initial magnetic susceptibility, saturation magnetostriction, saturation magnetization, and Young's modulus at unmagnetized state, respectively.

The Young's modulus at unmagnetized state vs. composition curve shows two maxima at about 25∼30 and 60 %Co and one minimum at about 50 %Co in the α phase range, and then falls considerably up to its boundary (at about 80 %Co). The modulus recovers in the $\alpha+\gamma$ phase range, but it decreases again in the narrow ε (hexagonal close-packed) phase range.

The marked discrepancies found between the results of the present dynamical measurements and those of the previous statical measurements by Honda and Tanaka on the ΔE effect and Young's modulus at unmagnetized state are shown to be due to differences in purity and in treatments of the specimens as well as to differences in the state of stress at the time of measurements of the specimens.

It is also shown that, with an addition of cobalt to iron, the density increases approximately hyperbolically up to cobalt, except for a small discontinuity near 80 %Co, and the initial magnetic susceptibility exhibits a sharp maximum near 50 %Co and a flat minimum at 65∼75 %Co.

I. Introduction

The only available data on Young's modulus and its variation with magnetization, namely, the so-called ΔE effect, measured in the whole composition range of iron-cobalt alloys, are those obtained on the specimens at lathe-machined state with the statical method of bending by Honda and Tanaka(1) more than thirty

* The 983rd report of the Research Institute for Iron, Steel and Other Metals.

(1) K. Honda and T. Tanaka, Sci. Rep. Tôhoku Univ., **15** (1926), 1.

years ago. Young's modulus at unmagnetized state, E_0, vs. composition curve obtained by them is shown in Fig. 1, which contains also the curve measured by Nishiyama(2) using the same method with annealed alloy specimens in the

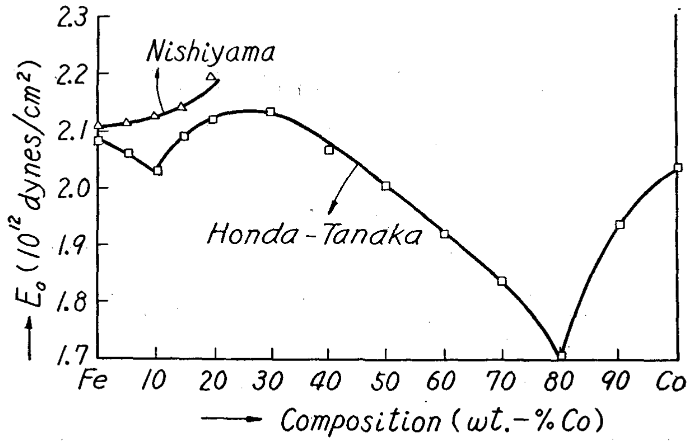

Fig. 1. Young's modulus at unmagnetized state, E_0, vs. composition curves of iron-cobalt alloys, obtained by Honda and Tanaka(1) and by Nishiyama(2) with the statical method of bending.

composition range up to 20 %Co. A minimum centered at 10%Co found by Honda and Tanaka is not seen in Nishiyama's curve. The $\Delta E/E_0$ vs. H curves ($\Delta E = E - E_0$, where E is Young's modulus at magnetized state, and H is the effective

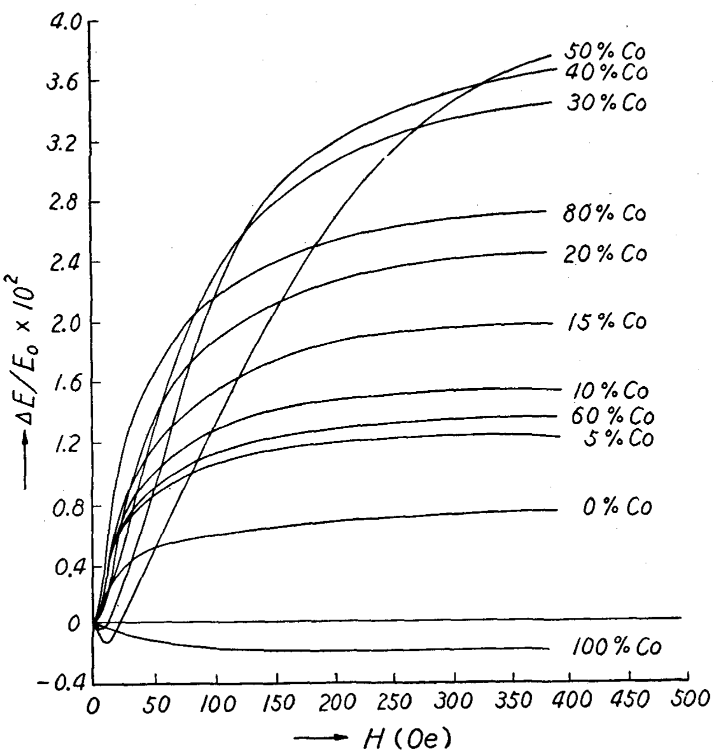

Fig. 2. $\Delta E/E_0$ vs. H curves measured with iron-cobalt alloy specimens in lathe-machined state by Honda and Tanaka(1) using the statical method of bending.

(2) Z. Nishiyama, Sci. Rep. Tôhoku Univ., 18 (1929), 359.

magnetic field) measured by Honda and Tanaka are reproduced in Fig. 2, which shows that the ΔE effect of pure cobalt is completely negative in magnetic field up to 400 Oe. This is quite unreasonable in view of the domain theory which predicts that the saturation value of the ΔE effect is always positive (or zero).

On the other hand, there are several inconsistencies between the experimental results on the ΔE effect so far obtained with a statical method and with a dynamical one. Although some of the inconsistencies surely originate from differences in purity and in treatment of the specimens employed, a remarkable inconsistency may be brought about by the difference in the state of stress in the specimens. For example, the statical method of bending, which usually requires a pretty heavy dead load as well as pretty heavy measuring loads and establishes a complicated state of stress in the specimen, yields a conspicuous negative minimum extending over a wide range of magnetic field in the $\Delta E/E_0-H$ curve of nickel,[3] which is not found in the curve measured with the dynamical method requiring no dead load and only very small stress for measurements and producing a simple state of stress in the specimen.[4~7] Also, for cobalt, the statical measurements by Honda and Tanaka[1] give an unreasonable negative ΔE effect, as mentioned above, while the dynamical measurements[4,7] show a reasonable positive one. It is to be noted, further, that, the values of Young's modulus at unmagnetized state, E_0, as measured with the statical method and with the dynamical one may also be different, since, according to the domain theory, E_0 is determined by the ΔE effect.

Thus, the dynamical measurements of Young's modulus and the ΔE effect with annealed specimens in the whole composition range of iron-cobalt alloys may be of value. We have made such measurements, and also the measurements of the densities and of some magnetic properties of iron-cobalt alloys.

II. Specimens

The specimens used are round bars, 4 mm in diameter and 10 cm in length, made of Armco iron, electrolytic cobalt, and iron-cobalt alloys containing 10, 20, 30, 40, 45, 50, 60, 70, 75, 80, 85, and 95%Co[8] (in balanced composition). The chemically analysed[9] compositions of Armco iron and electrolytic cobalt, which were also used as alloying elements, are shown in Table 1. The specimens were

(3) K. Honda, S. Shimizu, and S. Kusakabe, Phil. Mag., **4** (1902), 459; Phys. Z., **3** (1902), 380. K. Honda and T. Terada, Phys. Z., **6** (1905), 622; Phil. Mag., **13** (1909), 36.

(4) M. Yamamoto, Nippon Kinzoku Gakkai-shi, **5** (1941), 167 (in Japanese); Sci. Rep. Tôhoku Univ., **31** (1943), 101.

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

(6) M. Yamamoto, Nippon Kinzoku Gakkai-shi, **6** (1942), 40 (in Japanese); Sci. Rep. RITU, **A7** (1959), 102.

(7) M. Yamamoto, Nippon Kinzoku Gakkai-shi, **12** (1948), No. 2-3 (in Japanese). M. Yamamoto and S. Taniguchi, Nippon Kinzoku Gakkai-shi, **B15**(1951), 357 (in Japanese); Sci. Rep. RITU, **A7** (1955), 35.

(8) In this paper, the compositions of alloys are expressed in weight percent cobalt.

(9) The chemical analysis was done by the staff of the chemical analysis laboratory of our Research Institute.

prepared as follows:— The alloying elements balanced in a desired ratio were melted and mixed in an alumina crucible set in a Tammann or carbon tube furnace, with hydrogen gas burning over the surface of the melt. Then, the melt was cast into a metal mold, 5 mm in diameter, and the ingot thus made was lathe-machined to a round bar. The accurate dimensions of the specimens are

Table 1. Chemical analysed contents (in weight percent) of impurity elements in the pure metal used.

Metal	Fe	C	P	S	Si	Mn
Armco iron	—	0.03	0.016	0.032	0.03	0.06
Electrolytic cobalt	1.12	Trace	—	—	0.075	—

given in Table 2. The specimens, previously annealed at 1000°C for an hour in hydrogen atmosphere, were again annealed at the same temperature for the same duration in a vacuum before the present measurements. It is to be noted that the specimen of Armco iron was studied previously by the present author[(6)] in connection with the ΔE effect of iron-nickel alloys.

As is well known, the iron-cobalt system involves three solid solutions, α, γ, and ε, which have, respectively, body-centered cubic, face centered cubic, and hexagonal close-packed structures. However, various opinions have been proposed concerning the location of the boundaries of the mixture phases, $\alpha+\gamma$ and $\gamma+\varepsilon$. As for the $\alpha+\gamma$ phase, for instance, Masumoto[(10)] claimed a narrow range of 1~2 %Co around 78 %Co at 600°C, Andrews and Nicholson[(11)] a rather wide range of 74~81 %Co at 500°C, and lately Ellis and Greiner[(12)] also a wider range of 76.5−88.5%Co at 600°C. Such inconsistencies may have been caused by differences in method of determination employed, in purity of the specimens, and, particularly, in treatments of them. Actually, however, the structures at ordinary temperatures of iron-cobalt alloy specimens annealed at 1000°C correspond better to the phase diagram proposed by Masumoto,[(10)] according to which, the α phase extends from iron up to near 80 %Co, around which there is a narrow range of the $\alpha+\gamma$ phase, and next comes the γ phase extending up to about 95 %Co, arround which the narrow $\gamma+\varepsilon$ phase range is found, the rest being the ε phase. In view of the above-mentioned Masumoto's phase diagram as well as the experimental results described below, it can be said that our specimens containing less than 75 %Co belong to the α phase, the 80 %Co alloy specimen to the $\alpha+\gamma$ phase, the 85 and 95 %Co alloy specimens to the γ phase, and the cobalt specimen naturally to the ε phase. It is also certain that the specimens containing 40~ 60 %Co are ordered to a considerable extent.[(13)]

(10) H. Masumoto, Sci. Rep. Tôhoku Univ., **15** (1926), 450.
(11) J. H. Andrews and C. G. Nicholson, ***First report of the Alloy Steels Research Committee***, (1936), p. 93.
(12) W. C. Ellis and E. S. Greiner, Trans. Amer. Soc. Metals., **29** (1941), 415.
(13) M. Hansen, ***Constitution of Binary Alloys***, McGraw-Hill (1958), p. 471.

Table 2. Compositions and dimensions of the iron-cobalt alloy specimens used and miscellaneous measured data. ρ is the density and χ_0 the initial magnetic susceptibility. I_{max} is the intensity of magnetization measured at the highest (effective) magnetic field, H_{max}, which is practically equal to the saturation magnetization, I_s, and $(\Delta E/E_0)_{max}$ is the change of Young's modulus relative to that at unmagnetized state, E_0, measured at H_{max}, which is practically equal to the saturation values, $(\Delta E/E_0)_s$, excepting for pure cobalt. $(\Delta E/E_0)_-$ is the negative minimum value of the ΔE effect observed at weak fields. The data of the saturation magnetostriction, λ_s, measured by Masiyama,[22] are also tabulated.

Specimen No.	Composition wt.-% Co	Length (cm)	Diameter (cm)	ρ (g/cm^3)	χ_0	I_{max} (C.G.S.)	H_{max} (Oe)	$(\Delta(E/E_0)_-$ $\times 10^2$	$(\Delta E/E_0)_{max}$ $\times 10^2$	$E_0 \times 10^{-12}$ dynes/cm	$\lambda_s \times 10^6$
1	0	9.990	0.3939	7.892	7.2	1674	844	−0.035	0.2336	2.091	−8.83
2	10	10.000	0.3967	7.897	9	1791	840	−0.05	0.5720	2.100	16.10
3	20	9.995	0.3970	7.931	19	1860	836	−0.06	1.416	2.162	26.59
4	30	10.010	0.3979	7.956	21	1890	835	−0.13	3.118	2.190	41.80
5	40	10.045	0.3980	7.989	44	1887	836	−0.09	9.43	2.086	66.05
6	45	11.435	0.3983	8.011	47	1832	854	0	17.412	1.859	68.2*
7	50	10.020	0.3977	8.038	62	1856	837	0	2.10	1.745	70.20
8	60	10.050	0.3981	8.114	16.0	1815	839	−1.2	5.75	2.006	75.10
9	70	10.035	0.3971	8.255	9.1	1723	843	−2.1	3.44	1.869	90.30
10	75	10.020	0.3968	8.348	12.5	1682	845	−0.8	4.35	1.838	—
11	80	10.010	0.3966	8.440	6.4	1426	857	−0.50	1.124	1.553	—
12	85	10.010	0.3966	8.478	7.6	1530	852	−0.12	0.697	1.643	—
13	95	10.020	0.3971	8.684	11	1456	855	−0.03	0.716	1.919	—
14	100	9.840	0.4014	8.810	1.1	853	881	0	0.1680	1.890	—

* An interpolated value.

III. The density

In the first place, the densities of the specimens were measured by the hydrostatic method.[14] The measured data are given in Table 2 and also plotted against the composition in Fig. 3, in which the data measured previously by Preuss,[15] by Nishiyama,[2] and by Kussmann, Scharnow, and Schulze[16] are also shown for comparison. With an addition of cobalt to iron, the density increases approximately hyperbolically up to cobalt, except for a small discontinuity near 80%Co, namely in the range of the $\alpha+\gamma$ phase, which is also seen in the data obtained by Kussmann *et al.*

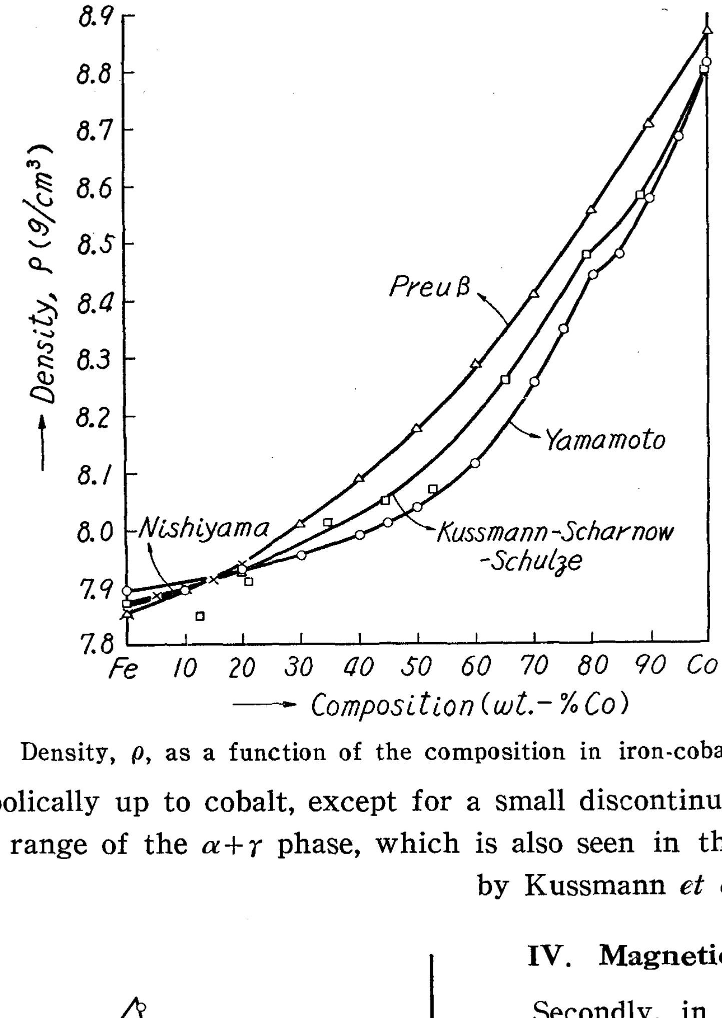

Fig. 3. Density, ρ, as a function of the composition in iron-cobalt alloys.

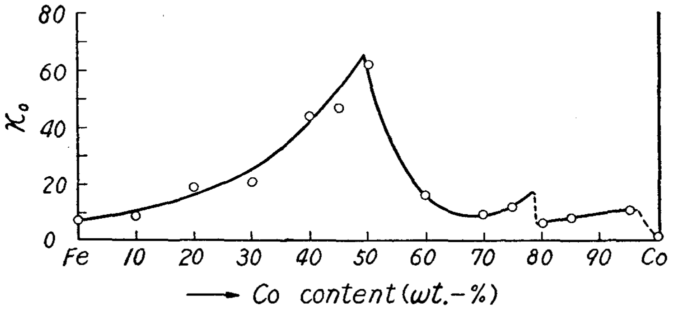

Fig. 4. Initial susceptibility, χ_0, as dependent on the composition in iron-cobalt alloys.

IV. Magnetic properties

Secondly, in order to get a knowledge of general magnetic characteristics of the specimens, the initial magnetic susceptibilities, χ_0, and the magnetization curves in the field range up to 900 Oe were measured by the ballistic galvanometer method. χ_0 and the intensity of magnetization

(14) M. Yamamoto, Nippon Kinzoku Gakkai-shi, **11** (1947), No. 11~12 (in Japanese): Sci. Rep. RITU, **A2** (1950), 871.
(15) A. Preuss, Dissertation, Zürich (1912).
(16) A. Kussmann, B. Scharnow, and A. Schulze, Z. techn, Phys., **13** (1932), 449.

even then, the sensitivity is 20~30 folds greater than that in aqueous solution.

(3) Effect of coexisting elements

The extraction of the oxine salt of manganese with organic solvents can be successfully carried out in the pH range of 7.2~12.5 and most of the interfering elements can be eliminated by the selection of the pH for the extraction. Aluminium does not interfere with this extraction even if present in the amount of 2 mg to 20 γ of manganese, but iron and copper interfere when present in the amount of 1 mg to 20 γ of manganese. In this case, these interfering elements must be removed by the extraction of their oxine complex salts with chloroform from acid solution.

3. Determination of copper

(1) Wave length and gas pressure

A solution containing 30 γ of copper was placed in a separatory funnel, 2 ml of oxine solution was added, the pH was adjusted to 3~5 by addition of ammonia water (1+1), and the whole volume was made up to 10 ml. This solution was extracted with 10ml of methyl isobutyl ketone or other organic solvents and the optimum gas pressure for the flame photometric analysis of copper in the extract solution was examined.

Copper gives spectral lines at 324.8 and 327.4 mμ the former being stronger in intensity, and so this was used for the measurement of the emission intensity.

Examination of optimum gas pressure for each of the solvents was made as follows :

(i) Extraction with methyl isobutyl ketone: The relationship between hydrogen pressure and emission intensity is shown in Fig. 7–I. At any oxygen pressure the maximum intensity was obtained at hydrogen pressure of 0.75~1.0

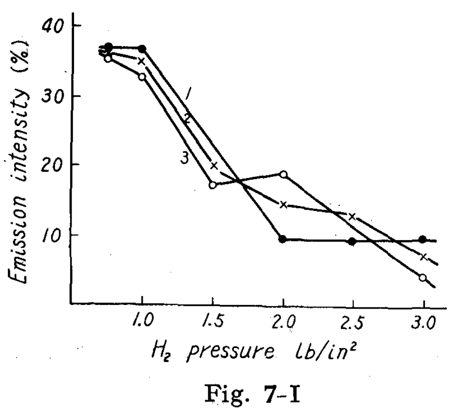

Fig. 7-I

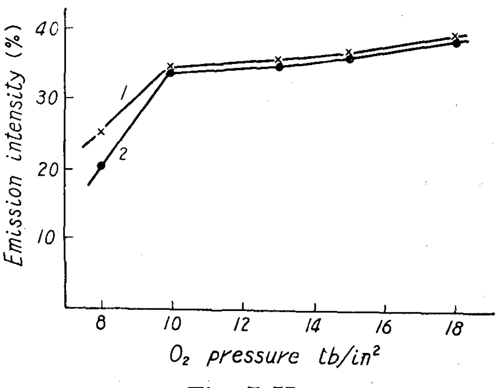

Fig. 7-II

Fig. 7–I. Relation between H_2 gas pressure and the emission intensity of copper spectal line.

30 γ Cu was extracted in methyl isobutyl ketone 10 ml and the intensity was measured at 324.8 mμ with slit width of 0.10 mm.

O_2 pressure was kept at (1) 15 lb/in^2, (2) 13 lb/in^2 and (3) 10 lb/in^2.

Fig. 7–II. Relation between O_2 gas pressure and the emission intensity of copper spectral line at 324.8 mμ.

Cu 30 γ was extracted in 10 ml methyl isobutyl ketone. slit width 0.10 mm. H_2 gas was kept at (1) 0.75 lb/in^2 and (2) 1.0 lb/in^2

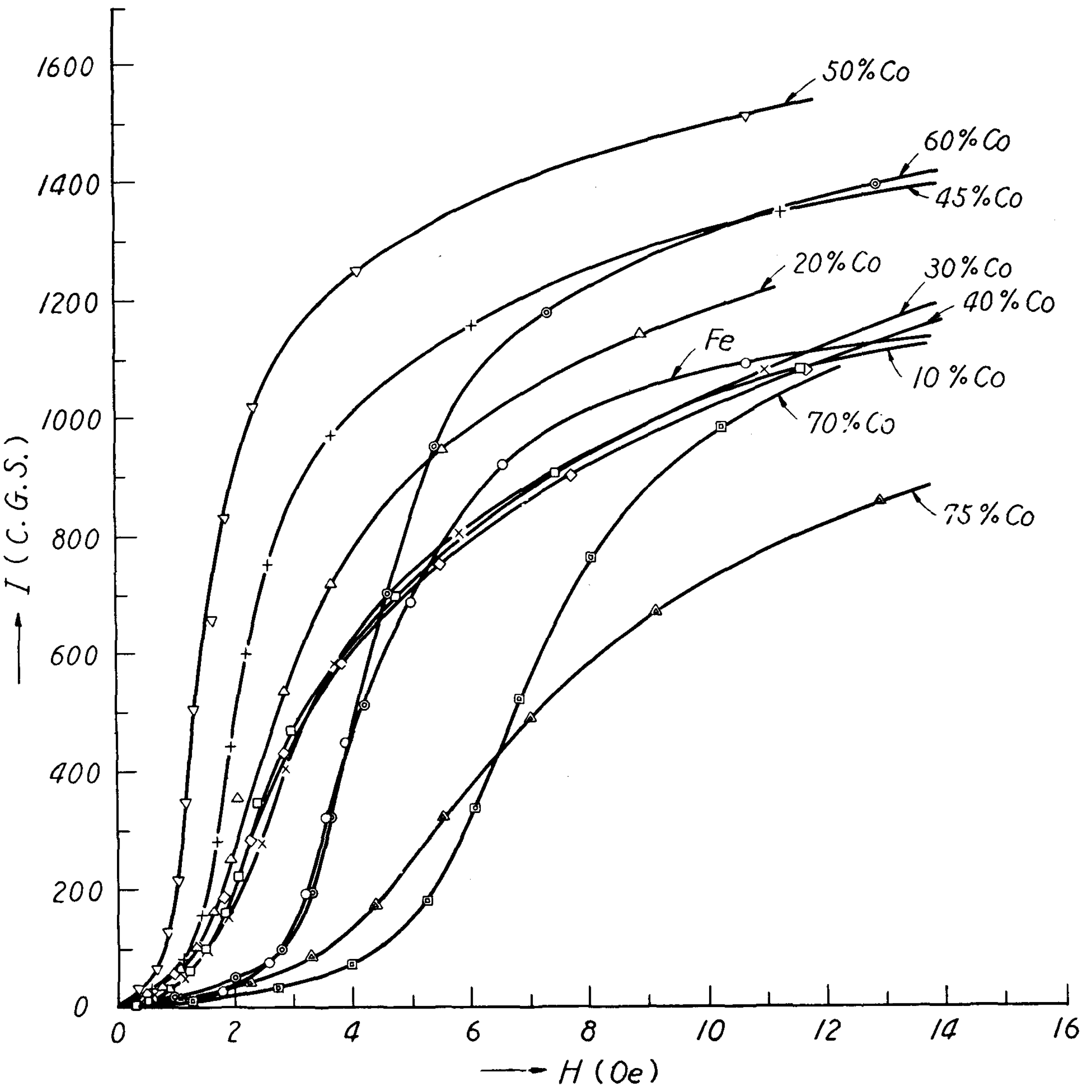

Fig. 6 (a). Magnetization curves at low fields of body-centered cubic iron-cobalt alloys.

A. ΔE effect as a function of the magnetic field or magnetization

The $\Delta E/E_0$ *vs.* H (effective magnetic field) curves are shown in Figs. 7, 8, and 9, and the $\Delta E/E_0$ *vs.* I (intensity of magnetization) curves are shown in Figs. 10 and 11.

Fig. 7 shows that the ΔE effect of the Armco iron specimen used here reveals a negative minimum at weak fields and a more or less conspicuous secondary rise just before saturation, as described previously.(7) The secondary rise of the ΔE effect near saturation was not observed with alloys containing more than 10%Co. On the other hand, the negative ΔE effect occurred at weak fields in most alloys with the excepting of 45 and 50%Co alloys and pure cobalt, as seen from Fig. 8 (b), 10, and 11. The negative minimum values, $(\Delta E/E_0)_-$, are tabulated in Table 2 and plotted against the composition in Fig. 12. As was pointed out already by the present author,(5~7,19) the magnetic field where the $(\Delta E/E_0)_-$ value

(19) M. Yamamoto and S. Taniguchi, Nippon Kinzoku Gakkai-shi, **18** (1954), 584 (in Japanese); Sci. Rep. RITU, **A8** (1956), 193.

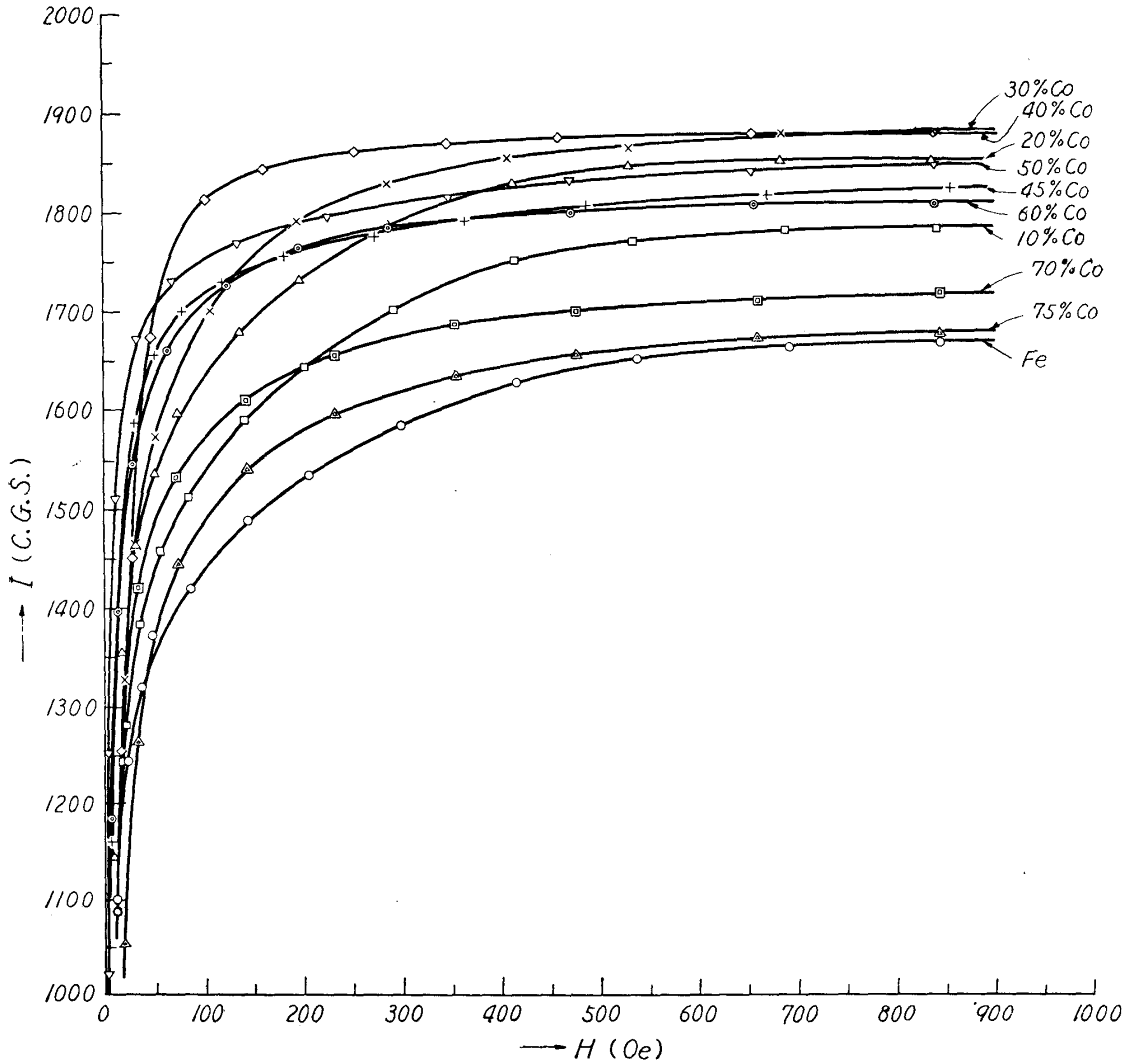

Fig. 6 (b). Magnetization curves at high fields of body-centered iron-cobalt alloys.

is located is approximately equal to that where the total or differential susceptibility becomes maximum, which may be seen from the comparison between the $\Delta E/E_0-H$ or $\Delta E/E_0-I$ curves and magnetization curves (Fig. 6). In a separate paper[20], we will show that the negative ΔE effect occurring at weak magnetic fields or in a low magnetization range can be interpreted in terms of the domain wall stabilization by the induced uniaxial anisotropy.

The $\Delta E/E_0-H$ or $\Delta E/E_0-I$ curves (Figs. 7, 9, and 11) of pure cobalt shows a maximum and a minimum at intermediate fields or in an intermediate magnetization range, as was found previously by the present author.[4,7]

B. Composition dependence of the maximum measured values or the saturation values of the ΔE effect

The $\Delta E/E_0$ values measured at the highest measuring field, H_{max}, are given in Table 2. As may be seen from the $\Delta E/E_0-H$ curves shown in Figs. 7, 8, and

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

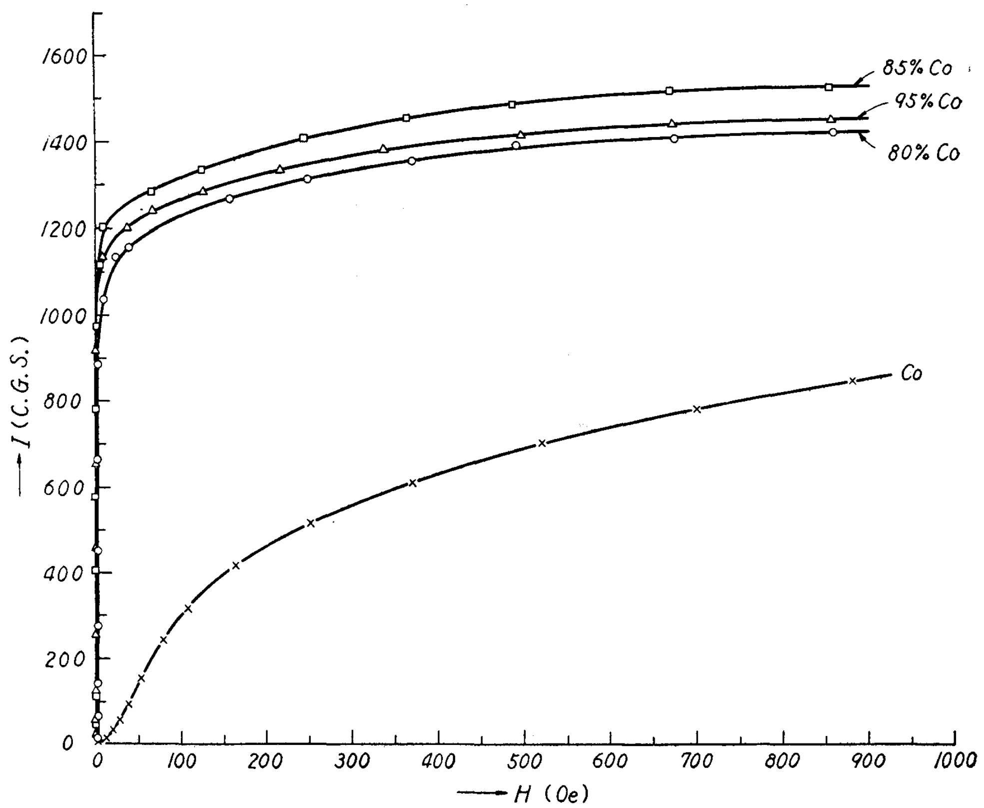

Fig. 6 (c). Magnetization curves of iron-cobalt alloys containing more than 80 %Co.

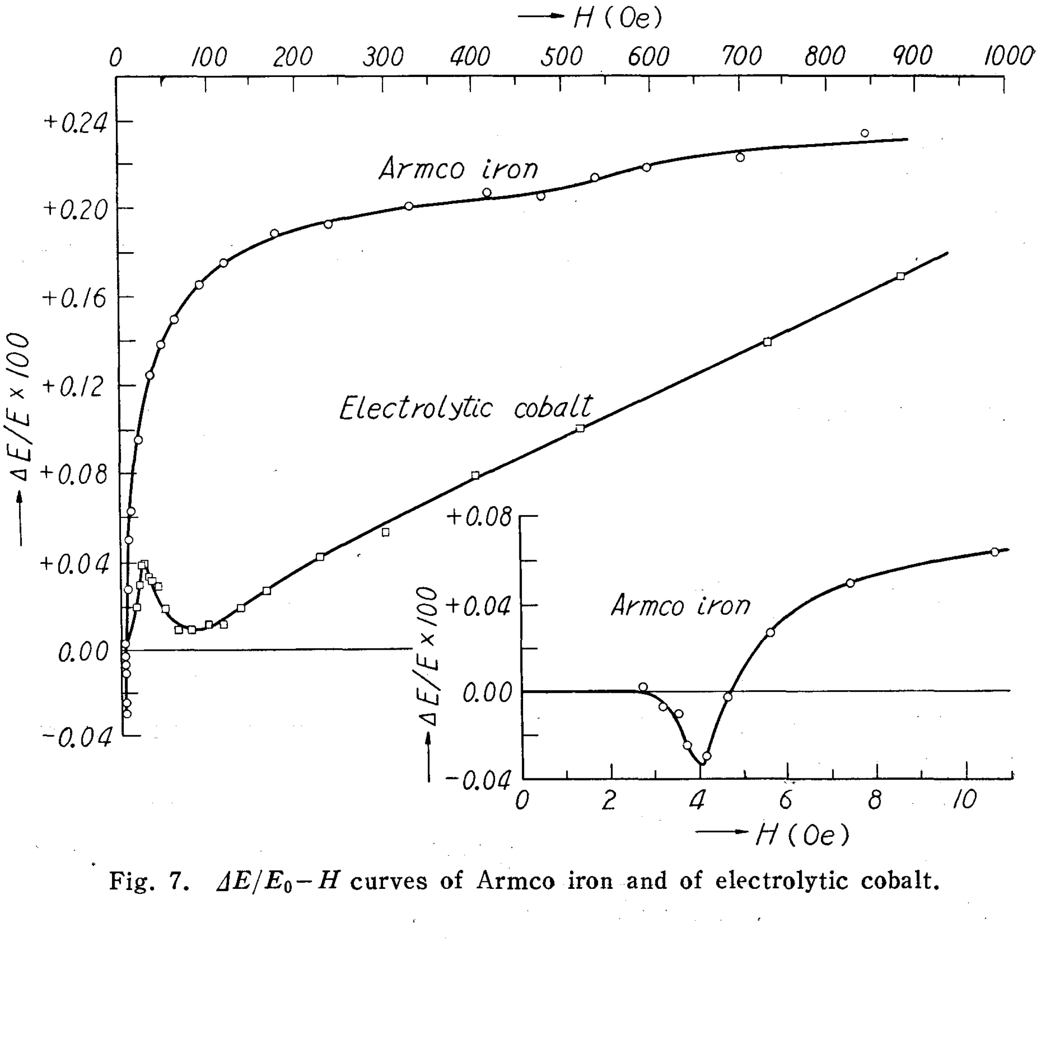

Fig. 7. $\Delta E/E_0 - H$ curves of Armco iron and of electrolytic cobalt.

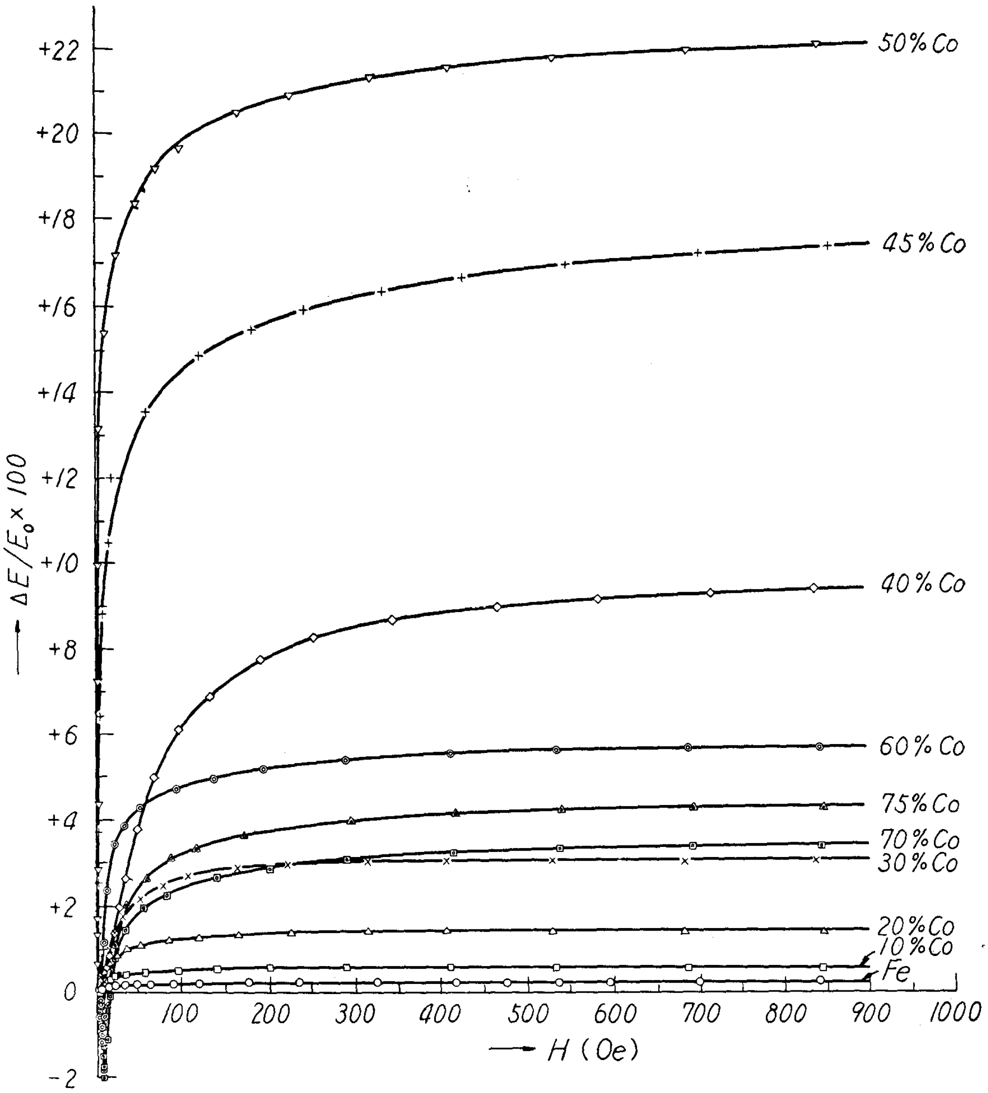

Fig. 8 (a). $\Delta E/E_0-H$ curves of body-centered cubic iron-cobalt alloys.

9, these maximum measured values, $(\Delta E/E_0)_{max}$, are approximate to the saturation values, $(\Delta E/E_0)_s$, except only for electrolytic cobalt. The composition dependence of $(\Delta E/E_0)_{max}$ is shown in Fig. 13. $(\Delta E/E_0)_{max}$ starts from a small value of about 0.2 % for Armco iron, and rises more and more quickly with increasing cobalt content, attaining to a high and sharp maximum over 22% near 50%Co. Afterwards, it falls quickly, but makes a more or less flat minimum of about 3% centered at about 65%Co. It, further, shows a discontinuous decrease in the narrow $\alpha+\gamma$ phase, takes a roughly constant value of about 0.7% in the γ phase range, and, in the ε phase range, finally falls to the value of about 0.17% for pure cobalt.

Our previous studies on the ΔE effect of nickel-copper,[5] iron-nickel,[6] nickel-cobalt,[7] and iron-aluminium alloys[19], all with cubic structures, indicate that the observed $(\Delta E/E_0)_s$ values are in a qualitatively good, and also in a quantitatively fairly good, agreement with values calculated from a formula.[21]

(21) This formula refers only to a contribution from the non-180° domain wall displacements.

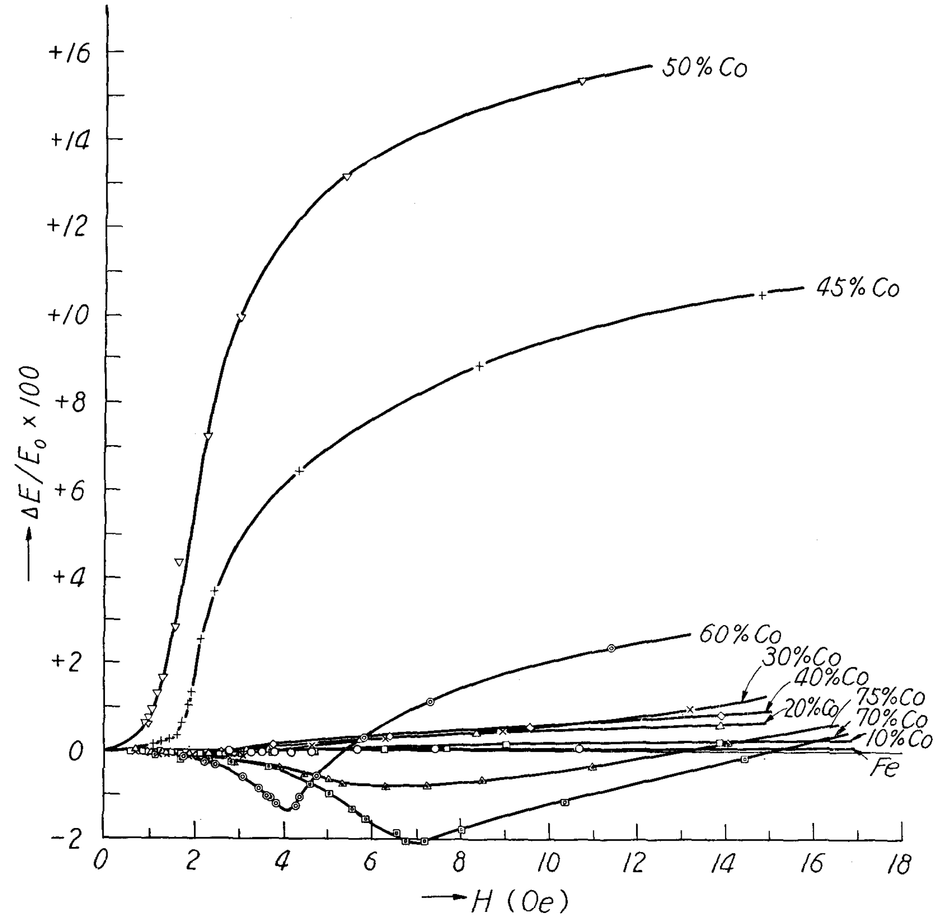

Fig. 8 (b). $\Delta E/E_0-H$ curves at low fields of body-centered cubic iron-cobalt alloys.

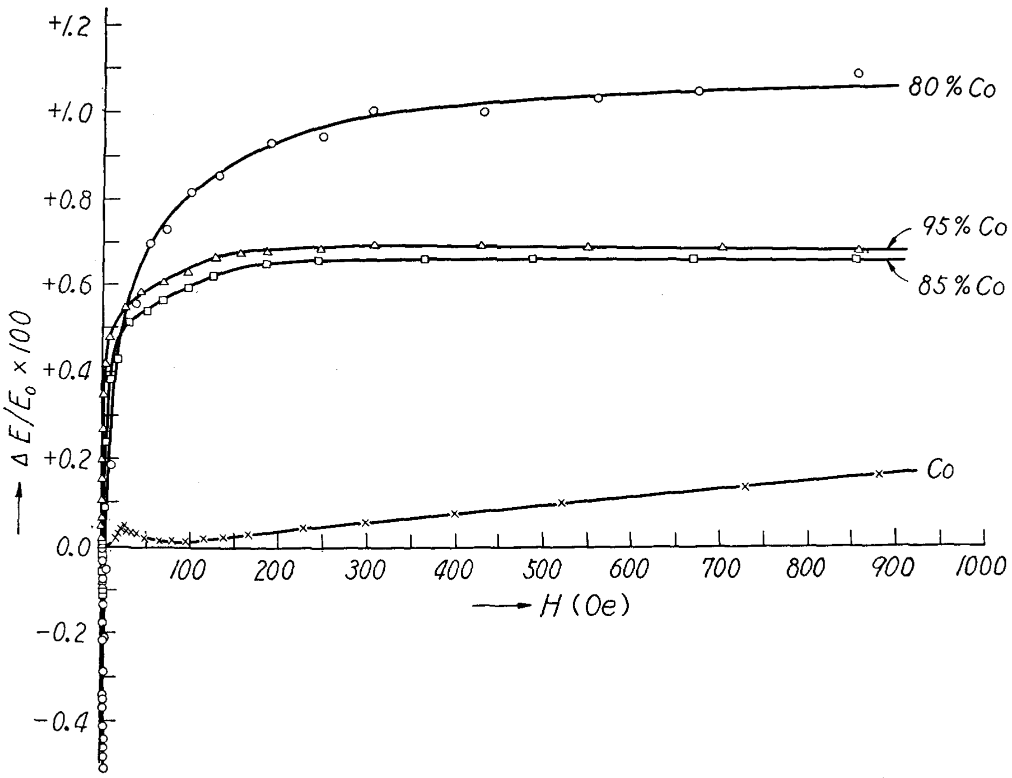

Fig. 9. $\Delta E/E-H$ curves of iron-cobalt alloys containing more than 80 %Co.

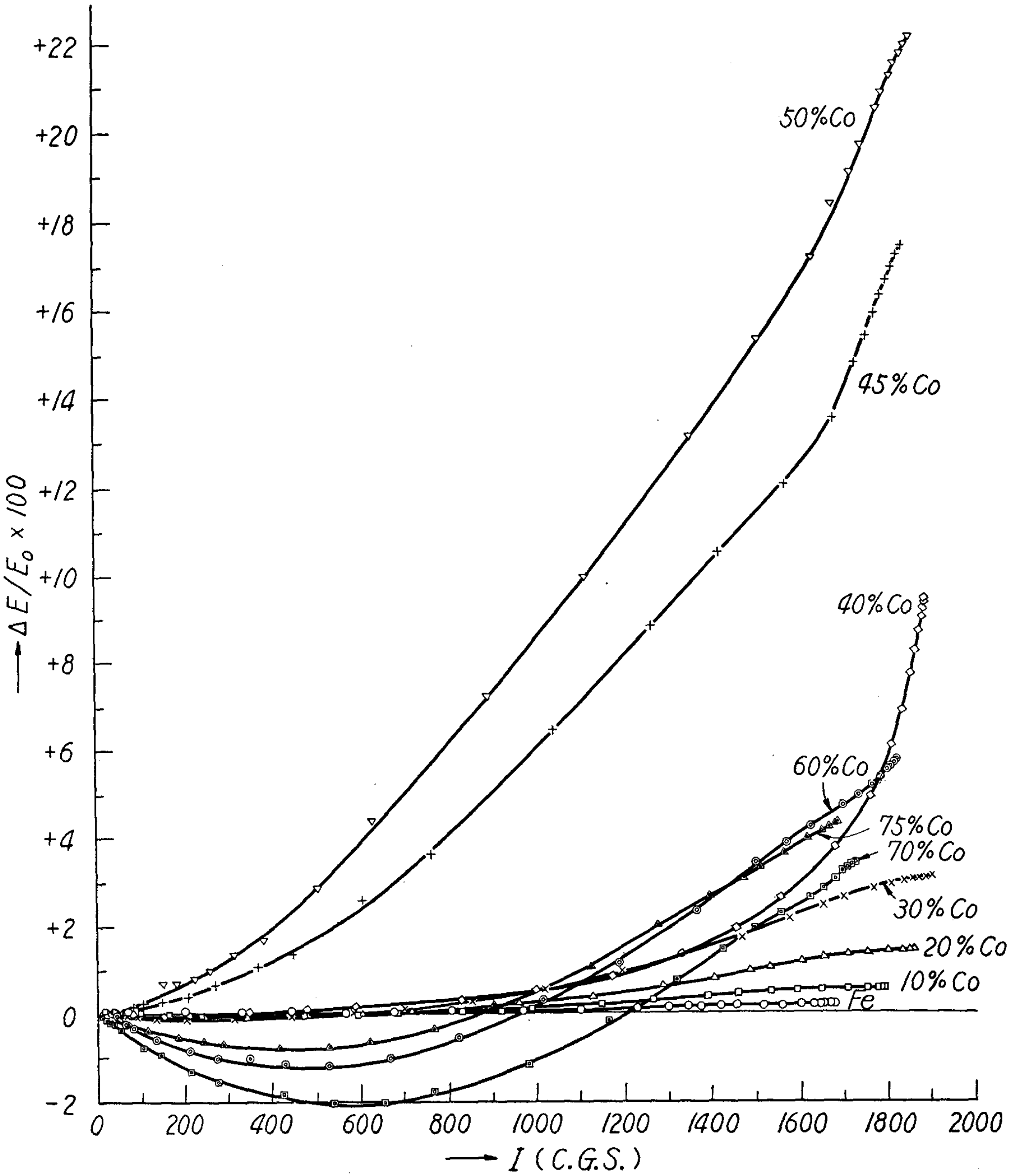

Fig. 10. $\Delta E/E_0 - I$ curves of body-centered cubic iron-cobalt alloys.

$$(\Delta E/E_0)_s = (0.7\chi_0\lambda_s^2 E_0/I_s^2)/(1-0.7\chi_0\lambda_s^2 E_0/I_s^2). \quad (1)$$

Where χ_0, I_s, λ_s, and E_0 are the initial susceptibility, saturation magnetization, saturation magnetostriction, and Young's modulus at unmagnetized state, respectively. The $(\Delta E/E_0)_s$ values calculated from Eq. (1) using the measured values of χ_0, $I_{max}(\simeq I_s)$, and E_0 (cf. Section VI) for our specimens of body-centered cubic (α phase) iron-cobalt alloys and the measured values of λ_s obtained by Masiyama[22], which are given in Table 2, are shown by crosses in Fig. 13, which indicates that the calculated and measured $(\Delta E/E_0)_s$ values agree with each other qualitatively well and also quantitatively fairly well in the case of body-centered cubic iron-cobalt alloys.

Fig. 13 also shows the measured $(\Delta E/E_0)_{max}$ data obtained by Honda and

(22) Y. Masiyama, Sci. Rep. Tôhoku Univ., **21** (1932), 394.

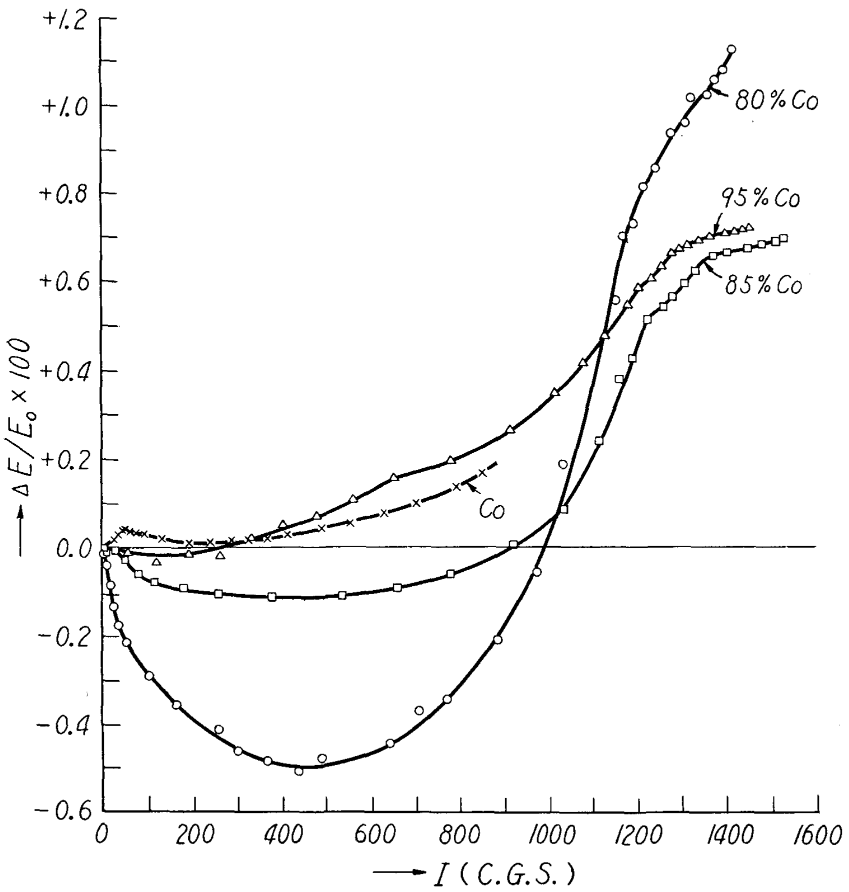

Fig. 11. $\Delta E/E_0-I$ curves of iron-cobalt alloys containing more than 80 %Co.

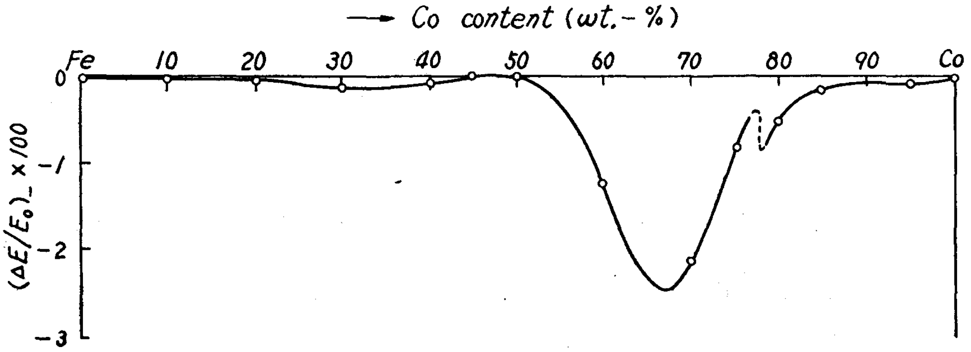

Fig. 12. The magnitude of the negative ΔE effect occurring at low fields, $(\Delta E/E_0)_-$, as a function of the composition in iron-cobalt alloys.

Tanaka[1] using the statical method of bending in magnetic fields up to 400 Oe. Their $(\Delta E/E_0)_{max}$ vs. composition curve starts from the value of about 0.7 % for pure iron and rises with increasing cobalt content. But, it shows a more or less constant value of about 4 % in the composition range from 30 to 50 %Co, and then decreases quickly. The trend of the curve beyond 60 %Co is uncertain on account of the lack of the measured points, but it finally attains the value of about -0.2% for pure cobalt. These data show a qualitatively roughly good, but a quantitatively bad agreement, with our measured data. Thus, the sharp and high

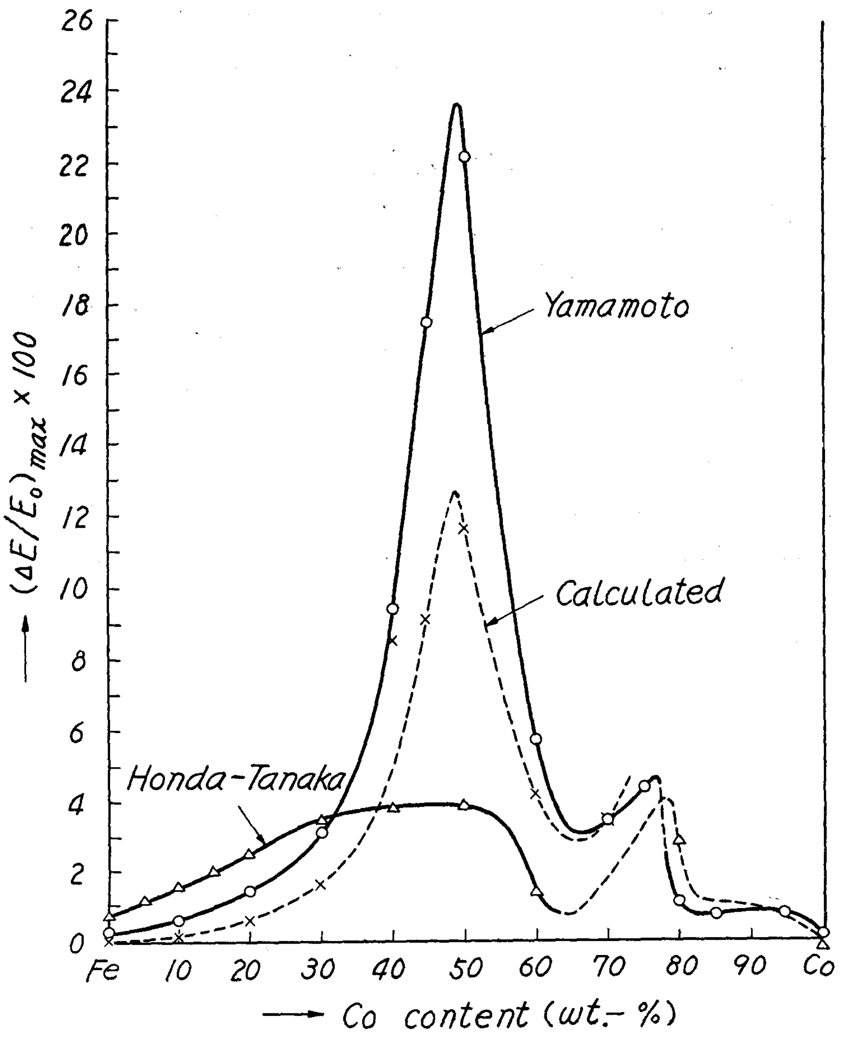

Fig. 13. Composition dependence of the maximum measured value of the ΔE effect, $(\Delta E/E_0)_{max}$, which is approximate to the saturation value except for pure cobalt. Honda-Tanaka's measured data for H=400 Oe with specimens in lathe-machined state are also plotted for comparison.

maximum amounting to over 22 % centered at about 50 %Co in our $(\Delta E/E_0)_{max}$ vs. composition curve corresponds to the flat and low maximum amounting to only 4 % in the composition range from 30 to 50 %Co in the curve of Honda and Tanaka. For pure cobalt, we measured a positive ΔE effect, while Honda and Tanaka found a negative one, which is unreasonable in view of the domain theory of the ΔE effect, as mentioned already in the introduction. It is to be added that the measurements by the statical method of elongation[(23)] show that the ΔE effect of cobalt under tension decreases by increasing tension but remains always positive. The discrepancies between the present data and Honda's ones will be discussed later.

(23) K. Honda, S. Shimizu, and S. Kusakabe, Phil. Mag., **4** (1902), 459.

VI. Young's modulus at unmagnetized state

Young's moduli at unmagnetized state, E_0, of the alloys have been determined using the relation

$$E_0 = 4l^2\rho f_0^2, \tag{2}$$

where l is the length, ρ the density, and f_0 the proper fundamental frequency of the longitudial vibration, of the specimen rod. Thus determined E_0 values are given in Table 2 and plotted against the composition in Fig. 14. E_0 as a function of the composition shows two maxima near 25 and 60 %Co and one minimum near 50 %Co in the α phase range, and then falls considerably up to the phase boundary. Then, E_0 recovers in the γ phase range, but it seemingly decreases again in the narrow ε phase range.

As seen from Fig. 14, the just-mentioned composition dependence of E_0 agrees with that found by Nishiyama[2] using the statical method of bending for the

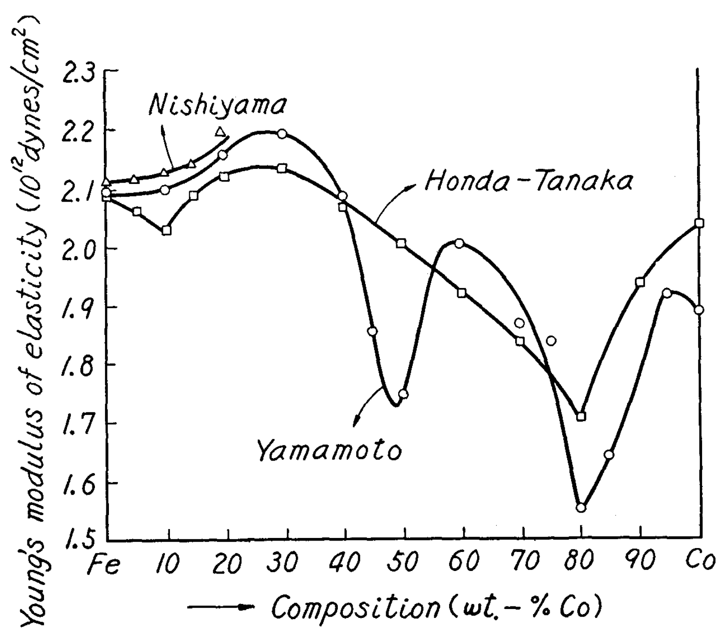

Fig. 14. Young's modulus at unmagnetized state, E_0, as a function of the composition in iron-cobalt alloys. Data obtained by Honda and Tanaka[1] and by Nishiyama[2] with the statical method of bending are also shown for comparison.

composition range below 20%Co, but it is quite different from that obtained by Honda and Tanaka[1] using the same method for the whole composition range. A minimum at 10 %Co observed by Honda and Tanaka are not seen in the present data as well as in Nishiyama's data, and a remarkable minimum centered at about 50 %Co found by the present measurements are not seen in Honda and Tanaka's data. Only one point of coincidence between the present data and Honda-Tanaka's ones is the presence of another remarkable minimum at about 80 %Co, namely, in the narrow $\alpha+\gamma$ phase range, although both data differ considerably as to the absolute magnitude of this minimum. Such differences between the present and

Honda-Tanaka's data will be discussed in the following section.

VII. Comparison with the static measurements by Honda and Tanaka

As described in V and VI, some considerable inconsistencies are present between the results of the present dynamical measurements and those of Honda and Tanaka's[1] statical ones on the ΔE effect and Young's modulus in iron-cobalt alloys. In order to clarify the origin of the inconsitencies, we compare the conditions of both measurements in the following.

In the first place, the purities of the specimens employed in both studies differ considerably. Iron and cobalt used as raw materials for alloying by Honda and Tanaka are much lower in purity than those used in the present study. In particular, iron and cobalt used by Honda and Tanaka contain 0.09 % carbon and 0.24 % carbon, respectively, while those in the present study contain 0.03 % carbon and trace of carbon, respectively, as seen from Table 1. Secondly, the treatments of the specimens are fairly different in both studies. Honda and Tanaka's specimens were in lathe-machined state, while our specimens were annealed twice after lathe-machined. Thus, Honda and Tanaka's specimens may have involved large internal stress, at least, in the surface layer.

However, the primary cause may be the difference in the state of stress in the specimen at the time of measurement in both studies. Statical methods usually require heavy dead load to be applied beforehand to the specimen and also pretty heavy measuring loads, while dynamical methods require no dead load and only very small stress for measurements. Accordingly, the statical method determines Young's modulus and its change under finite stress, while dynamical one measures those under zero stress. It is already known from theory as well as from experiments that Young's modulus and the ΔE effect of a ferromagnetic substance are changed by stress and that such changes are large for the substance with large magnetostriction. Moreover, it is to be noticed that the state of stress in the specimen subjected to bending is complex, while that in the specimen forced to longitudinal vibration is very simple. The effect of this difference in the state of stress in the specimen on the ΔE effect will be considered in a separate paper.[21]

Summary

With annealed iron-cobalt alloys covering the whole composition range, Young's moduli and their variation with magnetization (the ΔE effect) in magnetic fields up to 900 Oe have been measured at ordinary temperatures using the method of magneto-strictively excited longitudinal vibration. In connection with this, the density and ferromagnetic properties have also been determined.

It has been found that the negative ΔE effect occurs at weak magnetic fields in most alloys excluding 45~50 and 100 %Co. The absolute magnitude of the negative minimum of the ΔE effect is, at most, of the order of 0.1% in the alloys containing less than 45 %Co, while it amounts to more than 2 % in alloys containing

65~70%Co, and afterwards it decreases with increasing cobalt content. The maximum measured values of the ΔE effect, $(\Delta E/E_0)_{max}$, which are approximate to the saturation values, $(\Delta E/E_0)_s$, excepting only for pure cobalt, are all positive in the whole composition range of the alloys. The $(\Delta E/E_0)_{max}$ vs. composition curve starts from a small value of 0.2 % for pure iron, and rises more and more quickly with increasing cobalt content, attaining a very sharp and high peak of 22.10% at 50%Co. Afterwards, it falls quickly, but makes a more or less flat minimum of about 3 % centered at 65 %Co. It, further, shows a discontinuous decrease in the narrow α (body-centered cubic) + γ (face-centered cubic) range (at about 80%Co), takes a roughly constant value of about 0.7 % in the γ phase range, and finally, falls to the value of about 0.17 % for pure cobalt in the ε (hexagonal close-packed) phase range. The composition dependence of $(\Delta E/E_0)_{max}$ or $(\Delta E/E_0)_s$ in the α phase range is shown to agree qualitatively very well and also quantitatively fairly well with the results of calculation by a formula

$$(\Delta E/E_0)_s = (0.7\chi_0\lambda_s^2 E_0/I_s^2)/(1-0.7\chi_0\lambda_s^2 E_0/I_s)^2.$$

where χ_0, I_s, λ_s, and E_0 are the initial magnetic susceptibility, saturation magnetization, saturation magnetostriction, and Young's modulus at unmagnetized state, respectively.

The Young's modulus at unmagnetized state vs. composition curve shows two maxima at about 25~30 and 60 %Co and one minimum at about 50 %Co in the α phase range, and then falls considerably up to its boundary. The modulus recovers in the γ phase range, but it decreases again in the narrow ε phase range.

The marked discrepancies found between the results of the present dynamical measurements and those of the previous statical measurements by Honda and Tanaka on the ΔE effect and Young's modulus at unmagnetized state may be shown to be due to differences in purity and in treatment of the specimens as well as to difference in the state of stress at the time of measurements in the specimens.

It was also found that, with an addition of cobalt to iron, the density increase approximately hyperbolically up to cobalt, except for a small discontinuity near 80 %Co, and that the initial susceptibility exhibits a sharp maximum 50 %Co and a flat minium at 65~75 %Co.