JOURNAL OF THE PHYSICAL SOCIETY OF JAPAN VOL. 17, SUPPLEMENT B-I, 1962
PROCEEDINGS OF INTERNATIONAL CONFERENCE ON MAGNETISM AND CRYSTALLOGRAPHY, 1961, VOL. I

Magnetic Anisotropy of Monocrystals of Alloys Fe-Co-Ni*

I. M. PUZEY
The Central Research Institute for Ferrous Metallurgy
2 Baumanskaja St. 9/23, Moscow, USSR

The anisotropy constant of fourteen f.c.c. monocrystals of Fe-Co-Ni alloys have been investigated as a function of composition, ordering and temperature.

An ordering process causes a decrease in positive anisotropy and an increases of negative anisotropy. Similar phenomenon has been observed in other alloys. Apparently it is a general law for all known ferromagnetic ordering alloys.

The boundaries between regions of positive and negative anisotropies are determined for ordered and for disordered state. The ordering expands the region of negative anisotropy and decreases the other two positive regions.

In the region between the boundaries corresponding to quenched as well as annealed conditions it is possible to change the sign of anisotropy by adjusting the annealing duration. In such alloys by some appropriate heat treatment in magnetic field we can bring the crystalline anisotropy to almost negligible value and make the hysteresis loop to be rectangular.

An ordering strongly influences the temperature dependence of the anisotropy constant. This may be observed especially in the alloys in the region between the boundaries for the quenched and annealed conditions.

Introduction.

In 1929 Elmen[1] and Masumoto[2] discovered some region of Fe-Co-Ni alloys possessing specific properties:

a) Constant permeability at low induction.
b) Peculiar shape of hysteresis loop.

These alloys were called "Perminvar."

Bozorth and Dillinger's investigations[3] showed that the Perminvar is sensitive to magnetic treatment. Namely, after magnetic treatment the hysteresis loop is narrowed and become rectangular.

McKeehan[4] investigated the anisotropy for eight monocrystals of Fe-Co-Ni alloys in the region of f.c.c. phase. In accordance with Shih's data[5] for Ni-Co alloys he established an approximate diagram of regions of positive and negative anisotropy of ternary alloys in high nickel compositions. However, because of the difficulties of the first selection of the compositions and the absence of data on the influence of ordering upon anisotropy, this diagram is insufficient. In McKeehan's diagram one cannot see clearly the displacement of the boundaries of anisotropy region for nickel content less than 50%. The sign of the anisotropy constant in the closed central part of the diagram is not clear.

The aim of this paper is:

1) to investigate the value and sign of the anisotropy energy in the region of f.c.c. phase;

2) to establish regions of positive and negative anisotropies for ternary Fe-Co-Ni system;

3) to investigate the influence of ordering upon the value and sign of the anisotropy constant and the disposition of the boundaries;

4) to obtain the dependence of the anisotropy constant on temperature and the influence of ordering upon this dependence.

Specimens and testing methods

Fourteen monocrystals were subject to investigation, compositions of which are shown in Table I.

The monocrystals were produced by the method of very slow cooling of melt in helium gas. The specimens had the spherical shape. The sizes of the spheres were from 8 to 11 ($\pm$0.0005) mm in diameter. These were worked out by two kinds of heat treatments:

1) Annealing from 650°C to 250°C through 500 hours;

2) Heating to 650°C within 1 hour, then quenching in water.

Hereafter the first treatment is called simply "annealing", the second "quenching."

* This paper was not read at the conference.

The torque acting on the monocrystals in magnetic field of 10,000 Oe was measured in 24 positions of the field in the plane (100). By means of Bessel's formulae the amplitude of fourth harmonic was calculated and the anisotropy constant was calculated. The temperature of specimens was measured by means of the Pt resistance thermometer. The accuracy of temperature reading was within 0.1°C. The testing

Table I. Compositions of monocrystal specimens which were investigated.

No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Fe%	11.1	25.0	30.0	40.0	40.0	36.3	30.0	24.0	50.0	40.0	32.8	50.0	7.5	12.5
Co%	12.5	15.0	10.0	5.0	10.0	13.4	20.0	26.0	15.0	25.0	32.6	25.0	92.5	87.5
Ni%	76.4	60.0	60.0	55.0	50.0	50.3	50.0	50.0	35.0	35.0	34.6	25.0	0	0

Table II. Anisotropy constant of monocrystals of Fe-CoNi after annealing in 10^3 erg/cm^3.

No.	Temperature °C.												
	—195	—150	—100	—50	20	50	100	150	200	250	300	350	400
1	—1.81	—1.80	—1.76	—1.72	—1.61	—1.52	—1.36	—1.15	—0.94	—0.76	—0.50	—	—
2	3.30	3.14	2.95	2.70	2.30	2.12	1.80	1.50	—	—	—	—	—
3	1.24	1.20	1.16	1.13	1.03	0.94	0.84	0.67	0.50	0.31	0.15	—0.03	—0.14
4	12.46	11.90	11.06	10.08	8.50	7.74	6.48	5.20	4.06	3.04	2.12	1.24	—
5	21.4	20.6	19.1	17.5	14.5	13.0	10.9	9.0	7.0	5.0	3.5	2.3	—
6	14.2	13.6	12.9	12.1	10.9	10.3	9.0	7.5	5.9	—	—	—	—
7	—4.0	—5.0	—6.2	—7.2	—8.3	—9.2	—10.0	—10.3	—10.3	—	—	—	—
8	—52.5	—50.6	—48.3	—45.7	—41.4	—39.3	—36.0	—31.7	—28.0	—24.0	—20.0	—16.0	—
9	103.6	96.8	84.0	68.6	50.4	43.6	33.0	23.6	16.0	10.6	6.2	—	—
10	19.4	18.3	16.5	14.2	10.6	9.0	6.3	4.0	2.0	—	—	—	—
11	—18.9	—18.1	—17.5	—16.3	—14.6	—13.8	—12.5	—11.1	—9.55	—8.1	—6.6	—5.3	—
12	—28.1	—27.3	—25.8	—24.2	—21.6	—20.4	—18.2	—16.0	—13.8	—11.6	—	—	—
13 14	856	—840	—816	—787	—740	—720	—676	—628	—575	—514	—448	—	—

Table III. Anisotropy constant of monocrystals of Fe-Co-Ni after quenching in 10^3 erg/cm^3.

No.	Temperature °C											
	—195	—150	—100	—50	20	50	100	150	200	250	300	350
1	—7.26	—7.34	—7.48	—7.50	—7.16	—6.84	—6.14	—5.24	—4.20	—3.12	—2.30	—1.59
2	7.62	7.20	6.77	6.00	5.37	5.00	4.38	3.77	3.19	2.63	2.08	1.53
3	4.98	4.80	4.57	4.29	3.81	3.60	3.26	2.96	2.68	2.40	2.12	1.85
4	21.10	20.04	18.56	16.80	13.92	12.66	10.62	8.64	6.82	5.06	3.44	2.08
5	39.2	37.3	34.4	31.1	26.4	24.2	20.5	17.0	13.4	10.0	7.6	4.7
6	30.7	29.4	27.0	24.3	20.3	18.6	15.8	13.1	10.5	8.3	6.3	4.6
7	8.60	8.20	7.72	7.12	6.04	5.56	4.80	4.10	3.40	2.80	2.26	1.80
8	—44.4	—43.6	—41.2	—38.6	—34.8	—33.2	—30.2	—27.0	—24.0	—20.5	—17.3	—
9	121.2	112.8	99.0	83.0	60.6	52.0	39.0	28.0	19.0	12.0	—	—
10	37.6	35.4	32.0	28.0	21.2	18.6	14.2	10.2	7.0	4.6	3.0	—1.8
11	—14.5	—13.8	—13.0	—12.1	—10.7	—10.0	—8.8	—7.6	—6.4	—5.2	—4.0	—3.0
12	—16.4	—15.7	—14.7	—13.8	—12.2	—11.4	—10.1	—8.9	—7.6	—6.3	—5.0	—

method is given in an earlier paper[6] which is omitted here.

Results of the measurements.

In Table II and III are given the results of the measurement of anisotropy constants for the monocrystals.

An ordering influences the temperature dependence of the anisotropy constant. In Figs. 1, 2 and 3 are given the curves for the anisotropy constant versus temperature for specimens 1, 3 and 7. In Fig. 1 quenched curve shows a minimum at −70°C. Apparently it is a result of the transition of minimum for Ni_3Fe[7] in the region of ternary alloys.

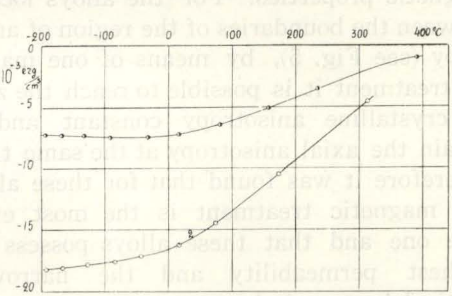

Fig. 1. Anisotropy constant of monocrystal 11.1% Fe, 12.5%Co, 76.4%Ni versus temperature after quenching (1) and annealing (2).

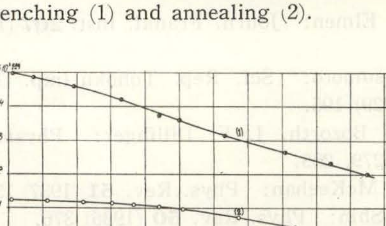

Fig. 2. Anisotropy constant of monocrystal 30% Fe, 10%Co, 60%Ni versus temperature after quenching (1) and annealing (2).

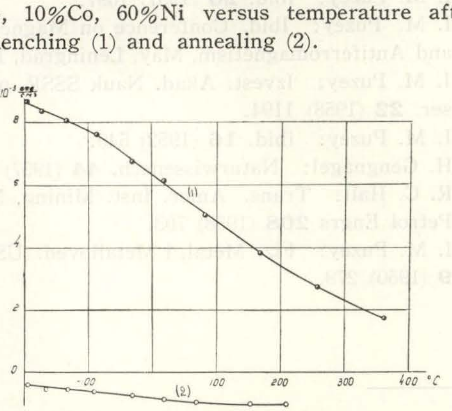

Fig. 3. Anisotropy constant of monocrystal 30%Fe, 20%Co, 50%Ni versus temperature after quenching (1) and annealing (2).

In Fig. 2 the change in sign of the anisotropy constant takes place at 350°C (for annealed state). Similar phenomenon was observed for specimen No. 10 at 300°C.

The change in sign of the anisotropy constant at high temperatures takes place for high nickel content and invar alloys Fe-Ni, and this change is due to magnetoelastic component in the energy of anisotropy[8]. Apparently the same causes the change in sign in Fig. 2.

An ordering strongly influences the temperature dependence of the anisotropy constants. This may be observed in the alloys in the region between the boundaries of anisotropy fields for the quenched and annealed conditions. In Fig. 3 it is seen that an ordering caused a change in sign of anisotropy constant and reversed the temperature dependence.

The monocrystals of Fe-Co alloys with 7.5 and 12.5% Fe are strongly anisotropic. The direction of easy magnetization is [111]. The

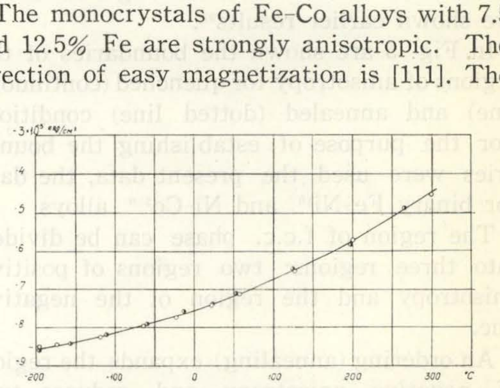

Fig. 4. Anisotropy constant of monocrystals 75%Fe (-○-○-) and 12.5%Fe (-○-○-) versus temperature.

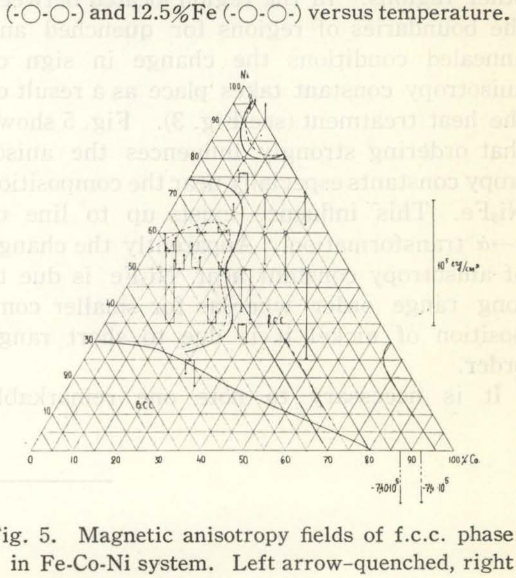

Fig. 5. Magnetic anisotropy fields of f.c.c. phase in Fe-Co-Ni system. Left arrow-quenched, right one-annealed states.

anisotropy constant at ordinary temperatures is equal to $-7.4 \cdot 10^5$ erg/cm^3 for both monocrystals. This circumstance must be taken into account in using these monocrystals for polarizing neutrons. In Fig. 4 the temperature dependence of the anisotropy constant of monocrystals is shown.

The present data give a possiibility of establishing the regions of anisotropy on the triangle of concentrations in Fe-Co-Ni system and the influence of heat treatments upon its disposition. In Fig. 5 the value and sign of anisotropy constant are shown by arrows. The left part is for disordered and the right part for ordered conditions. The anisotropy constant corresponds to the composition which is shown by a point on the middle between two near-lying arrows. The single arrows with a circle at the base are McKeehan's data. On the side of Ni-Co of the triangle Fe-Co-Ni are shown earlier results[9].

In Fig. 5 are shown the boundaries of the regions of anisotropy for quenched (continuous line) and annealed (dotted line) condition. For the purpose of establishing the boundaries were used the present data, the data for binary Fe-Ni[10] and Ni-Co[5,9] alloys.

The region of f.c.c. phase can be divided into three regions: two regions of positive anisotropy and the region of the negative one.

An ordering (annealing) expands the region of negative anisotropy and reduces two other regions. In the region located between the boundaries of regions for quenched and annealed conditions the change in sign of anisotropy constant takes place as a result of the heat treatment (see Fig. 3). Fig. 5 shows that ordering strongly influences the anisotropy constants especially near the composition Ni_3Fe. This influence exists up to line of $\gamma \rightarrow \alpha$ transformation. Apparently the change of anisotropy constant near Ni_3Fe is due to long range order whereas for smaller composition of nickel it is due to short range order.

It is necessary to note one remarkable regularity, namely, in the process of ordering the anisotropy constant changes as though the negative component of constant would arise. Therefore an ordering results in decreasing positive and increasing negative anisotropy. This phenomenon is observed in Fe-Ni[10], Fe-Co and Fe-Al[11,12,13] alloys and it is a general law for all known ferromagnetic ordered alloys.

After the magnetic treatment an axial anisotropy arises, which adds to the crystalline one. The total energy of anisotropy influences the magnetization process. The crystalline anisotropy decreases the level of the magnetic properties. For the alloys located between the boundaries of the region of anisotropy (see Fig. 5), by means of one magnetic treatment it is possible to reach the zeroth crystalline anisotropy constant and to obtain the axial anisotropy at the same time. Therefore it was found that for these alloys the magnetic treatment is the most effective one and that these alloys possess the highest permeability and the narrowest vertical hysteresis loop.

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