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On the Magnetic Shunt Characteristics of Fe-Ni-Cr Alloys and M. S. Alloy*

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Synopsis

For the purpose of improving the magnetic shunt alloys hitherto used, the magnetic properties of Fe-Ni-Cr alloys, containing 30~60% of Ni, 1~18% of Cr and having no allotropic transformation, were measured at various temperatures ranging from −50° to 100°. It has been found that those alloys with the magnetic transformation point of about 100° show excellent characteristics of magnetic shunt as follows : The permeability in 400 Oe at 0° are 5~20 and their temperature coefficient, 0.003~0.040, the permeability varying almost linearly with the temperature. And the authors have named them "M. S. Alloy".

I. Introduction

The magnetic intensity of a permanent magnet or a magnetic pole piece decreases with the rise of temperature, concequently, the intensity of magnetic field introduced between two poles of magnet decreases as the temperature is raised. In order to prevent this decrease, usually, in some part of the pole gap is placed a magnetic alloy having the property of remarkably reducing its permeability with the rise of temperature. If the alloy is suitable for the magnet, the magnetic field of the pole gap can be always kept constant irrespective of temperature. The alloy used for this purpose is called a magnetic shunt alloy. The characteristics of the magnetic shunt alloy are the suitable permeability and the large temperature coefficient in the temperature range used.

There are two kinds of alloys hitherto used for this purpose,(1)(2) the one(3) is a Ni-Cu alloy of Monel type, containing 70~90% Ni, 30~10% Cu, and a some of Fe or Mn as an addition; the other(4)(5) is an Fe-Ni alloy, containing about 29% Ni and a small amount of C, Cr, and Mn. However the former has a disadvantage in being too expensive because of the high content of Ni, and the latter has a less reproductivity as a defect, owing to the fact that it contains C, to maintain a fixed content of which in it is difficult and secondly it further has an allotropic transformation, in the cause of which its properties varies remarkably according

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(1) T. D. Yensen, Trans. Amer. Soc. Metals, **27** (1939), 797.

(2) Y. Shirakawa, "Special Magnetic Alloys and their Applications" Japan Institute of Metals, (1950).

(3) J. E. Kinnard, H. T. Faus, Trans. Amer. Inst. Elect. Eng., **44** (1925), 275 ; **49** (1930), 949.

(4) F. Stäblein, Z. Techn. Phys., **9** (1928), 145.

(5) H. Shimba, T. Aozagi, J. Japan Inst. Metals, **6** (1943), 444.

to the degree of working, the velocity of cooling and the lowest temperature for cooling and the holding time at that temperature.

Hence, the present writers have investigated on the magnetic shunt characteristics of Fe-Ni-Cr alloys for the purpose of improving the magnetic shunt alloys hitherto used, that is, with the view to obtaing alloys having less content of Ni than Ni-Cu alloys of Monel type and more reproductivity than Fe-Ni alloys.

The following is an abstract of the standard of Fe-Ni magnetic shunt alloys.

1. In $H=400$ Oe, the permeability μ_z at 0° is in the range of 6～14.
2. The temperature coefficient $\alpha_z=\frac{\mu_{-5}-\mu_5}{\mu_z\times 10}$ (μ_{-5} and μ_5 is permeability at $-5°$ and 5° respectively.) of μ_z is in the range of 0.008～0.020/°C.
3. The deviation δ from α_z of the temperature coefficient at each temperature α_t is within ±25% below $-30°$, ±10% between $-30°$～30° and ±25% above 30°, respectively.

II. Specimens

The materials used in preparing of alloys of Fe-Ni-Cr system were electrolytic iron of Nippon-Denkai-Seitetsisho, electrolytic nickel supplied by Inco Co. and metallic chromium; the results of chemical analysis of these metals is given in Table 1.

Table 1. Chemical Analysis of Metals Used.

Metals	Composition (%)										
	Fe	Ni	Cr	Co	C	Cu	Si	Mn	Al	P	S
Electrolytic Iron	—	—	none	—	0.05	none	0.00_8	0.00_4	0.02	0.00_{05}	0.00_3
Electrolytic Nickel	0.04_0	—	—	0.45	0.14	0.00_8	0.01_4	trace	0.03_3	trace	0.00_8
Metallic Chcomium	0.29	—	—	—	0.03	—	0.51	0.03	0.17	—	—

In the preparation of specimens a suitable proportion of these metals of 100 g is weighed, mixed and then melted under hydrogen atmosphere in an alumina crucible which was placed in a Tamman furnace, in melting them, 0.4% of Mn and 0.1% of Al were added as deoxidizer. The melt was taken out of the furnace together with the crucible, and then solidified. Next the crucible was destroyed and the alloy thus obtained was forged to a round rod about 7 mm in diameter under repeated annealing and finished with a lathe into a cylindrical rod 5 mm in diameter and 100 mm in length. The specimen thus made is then annealed at 1,000° for an hour in a high vacuum and cooled slowly in a furnace after the electric current had been switched off.

The results of the chemical analysis of the specimens used are shown in Table 2.

III. Method of Measurement

The magnetizing apparatus is schematically shown in Fig. 1. The specimen (S) is placed at the bottom of the glass tube (G_1) about 6 mm in inner diameter, being situated in the middle portion of uniform field in the magnetizing coil. To make

Table 2. Composition of Magnetic Shunt Alloys and Results of Measurements.

Specimen No.	Composition (%)		Field (Oe)	Permeability at 0° μ_z	Temperature Coefficient $\alpha_t \times 10^3$					Mean Temperature Range ΔT(°C)	Mean Temperature Coefficient $\bar{\alpha} \times 10^3$
	Ni	Cr			α_z	α_{10}	α_{20}	α_{30}	α_{40}		
1	30.57	7.30	300	11.7	16	17	17	15	12	0~28	17
			400	9.1	16	16	16	14	12	0~28	16
			500	7.6	16	16	15	13	11	0~31	15
2	31.82	5.19	300	19.5	6	7	8	8	10	0~20	7
			400	14.9	6	6	7	8	10	0~35	7
			500	12.3	7	7	7	8	9	0~30	7
3	31.86	7.39	300	15.0	8	10	11	11	13	−27~20	8
			400	11.4	8	8	9	10	14	−30~30	8
			500	9.5	7	8	10	11	13	−46~15	7
4	31.98	3.56	300	22.3	5	5	6	6	8	0~40	6
			400	17.0	5	5	6	6	7	0~43	6
			500	13.6	5	5	6	6	7	0~44	6
5	31.98	8.50	300	12.3	16	16	17	18	14	0~25	17
			400	9.6	15	15	17	17	12	0~30	16
			500	7.8	12	14	16	22	13	0~25	14
6	32	11*	300	6.2	41	30	17	6	2	0~9	37
			400	5.2	39	28	17	7	3	0~12	32
			500	4.7	37	25	15	8	4	0~11	31
7	32.05	5.68	300	19.0	7	8	8	9	10	−26~33	7
			400	14.6	7	8	8	8	10	−20~40	8
			500	11.9	7	7	8	9	9	−20~40	8
8	32.12	2.81	300	23.0	5	6	6	7	8	0~36	6
			400	17.8	6	6	6	7	7	0~47	7
			500	14.3	6	6	6	6	7	0~40	6
9	32.63	9.50	300	12.9	13	14	16	18	17	0~24	14
			400	10.0	12	13	14	17	17	0~29	14
			500	8.2	12	12	14	15	14	0~30	13
10	33.06	8.04	300	16.0	8	8	9	10	15	0~35	9
			400	12.2	8	8	9	9	14	0~38	9
			500	9.9	7	8	8	9	12	0~35	8
11	33.10	5.89	300	20.1	6	6	7	7	8	0~39	7
			400	15.4	6	6	7	7	8	0~39	7
			500	12.6	6	6	6	7	8	0~44	7
12	33.59	8.96	300	14.7	10	10	11	11	14	0~32	11
			400	11.5	9	9	9	12	14	0~35	10
			500	9.2	9	9	9	11	14	0~31	9
13	33.65	11.31	300	8.6	35	29	21	7	4	0~13	32
			400	6.7	34	30	20	8	4	0~17	30
			500	5.6	33	24	17	10	5	0~18	26
14	33.66	7.99	300	20.8	5	5	5	5	6	0~49	5
			400	15.8	5	5	5	5	5	0~52	5
			500	12.9	4	4	4	5	6	0~48	6
15	33.81	10.61	300	13.3	10	11	14	17	20	0~24	12
			400	10.3	11	11	12	16	17	0~19	10
			500	8.4	10	10	11	15	18	0~31	11

Table. 2. Cont.

Specimen No.	Composition (%)		Field (Oe)	Permeability at 0°	Temperature Coefficient $\alpha_t \times 10^3$					Mean Temperature Range	Mean Temperature Coefficient
	Ni	Cr		μ_z	α_z	α_{10}	α_{20}	α_{30}	α_{40}	$\overline{\Delta T}$(°C)	$\overline{\alpha}\times 10^3$
16	33.85	9.05	300	14.6	10	10	10	11	15	0~34	10
			400	11.1	9	9	9	10	15	0~37	12
			500	9.4	10	10	10	10	11	0~44	10
17	34.02	7.34	300	20.1	6	6	6	7	7	0~55	7
			400	15.3	6	6	6	6	7	0~55	7
			500	12.4	5	5	6	6	7	0~38	6
18	34.52	12.22	300	18.2	6	6	6	7	9	0~40	7
			400	13.8	6	6	6	7	9	0~37	6
			500	11.3	5	6	7	8	9	0~36	7
19	34.89	10.09	300	19.3	6	6	6	6	7	0~48	6
			400	14.7	5	5	5	6	7	0~47	6
			500	12.1	5	6	6	6	7	0~42	6
20	35	12*	300	16.6	9	10	10	12	13	0~27	10
			400	12.7	9	9	9	12	13	0~33	9
			500	10.5	9	9	9	10	12	0~31	9
21	35.68	5.76	300	31.0	3	3	3	3	3	0~69	3
			400	23.3	3	3	3	3	3	0~70	3
			500	18.7	3	3	3	3	3	0~80	3
22	35.76	35.8	300	36.2	2	2	2	2	2	0~95	2
			400	28.4	2	2	2	2	2	0~95	3
			500	22.8	1	1	1	1	1	0~92	2
23	35.87	7.63	300	24.9	3	4	4	4	4	0~79	4
			400	19.1	3	3	3	4	4	0~60	4
			500	15.5	3	3	3	3	4	0~65	4
24	36	10*	300	20.5	4	4	4	4	5	0~47	4
			400	15.6	4	4	4	4	4	0~48	4
			500	12.7	4	4	4	4	5	0~50	4
25	36	2*	300	42.7	2	2	2	2	2	0~100	2
			400	32.4	2	2	2	2	2	0~100	2
			500	26.0	2	2	2	2	2	0~100	2
26	36.12	9.57	300	23.1	3	3	3	4	4	-40~40	3
			400	17.6	3	3	3	3	4	-23~50	3
			500	14.3	3	3	3	3	4	-50~30	3
27	36.17	0.03	300	45.3	1	2	2	2	2	0~75	2
			400	33.8	2	2	2	2	2	0~75	2
			500	27.3	2	2	2	2	2	0~80	2
28	44.85	13.14	300	19.3	3	3	3	3	4	0~62	3
			400	14.7	3	3	3	3	3	0~61	3
			500	11.9	3	3	3	4	4	0~81	4
29	55	15*	300	22.0	4	5	5	5	5	0~53	5
			400	16.6	3	4	4	4	4	0~65	4
			500	13.5	4	4	4	5	5	0~57	5

* Charge Percentage

a search coil (S. C), a silk-covered copper wire about 0.1 mm in diameter is wound in 2 layers with 50 turns each round the part of the glass tube (G_1) corresponding to the middle portion of the specimen contained therein. The glass tube (G_1) is further put in another one (G_2) so as to prevent electric leakage due to moisture. Thus the search coil (S. C) is commonly used in the measurement of each specimen. In order to keep the temperature of the specimen uniform and constant during the measurement, the specimen is placed in a Dewar vessel (D), the water or alcohol filled in it being used for heating or cooling the specimen. A Cu-constantan thermocouple (J) is used for the measurement of temperature of the specimen and its high temperature junction is so arranged as to contact with the upper end of the specimen through the interior of a glass tube (G_3) holding the thermo-couple.

The intensity of magnetization was measured by the ballistic method, at 0~100° or at −50~100° especially for the three representative specimens. The constant of magnetizing coil (M. C) is 63.10/A. The measurement was carried out at enough, constant temperature both in heating and cooling, but the deviation of about ±0.5° could not be avoided as a millivoltmeter was used in the measurement of temperatures.

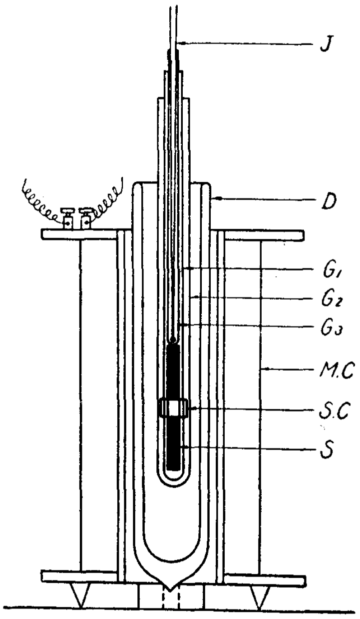
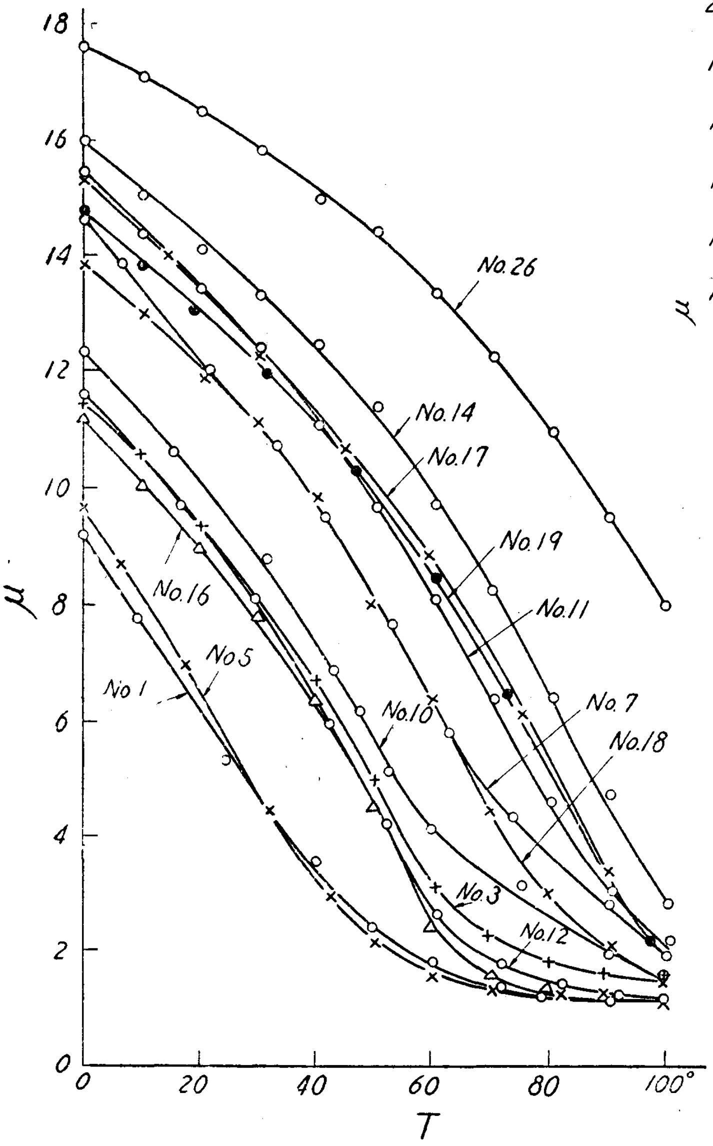


Fig. 1. Magnetizing Apparatus. (D) Dewar Vessel, (G_1) Glass Tube with Search Coil, (G_2) Glass Tube to make Search Coil water-tight, (G_3) Glass Tube holding Thermo-Couple (J) Cu-Constantan Thermo-Couple, (M. C) Mognetizing Coil, (S) Specimen, (S. C) Search Coil.

IV. Results of Measurement and Considerations

First the permeability curves for the magnetic field were obtained from magnetization curves measured, then permeability temperature curves in magnetic field of 300 Oe, 400 Oe and 500 Oe were obtained from permeability curves at different temperatures, some of the permeability-temperature curves in 400 Oe being shown in Fig. 2 (a) and (b). The permeability μ_z at 0°, for each field is shown in Table 2. In Table 2 is also shown the temperature coefficient α_t of the permeability in each field at 0°, 10°, 20°, 30° and 40° respectively which was obtained according to the standard from the permeability-temperature curves. Further μ_{-5}, the permeability at $-5°$ of the specimen in which the permeability was not measured at the same temperature was obtained by means of the extraporation of the permeability-temperature curve. In this table, $\overline{\Delta T}$ denotes the temperature range which is the length of the longest straight line beginning at 0° or passing through 0° for the three representative specimens, included in the region between two similar curves having the deviation of ±1% drawn against the permeability-temperature curve, and $\bar{\alpha}$ denotes the value $(\bar{\mu}_z-\bar{\mu}_t)/\bar{\mu}_z\cdot\overline{\Delta T}$ or the mean temperature coefficient. In

Table 3 is shown α_{-t}, the temperature coefficient at low temperatures. The deviation δ_t of temperature coefficient α_t from α_z obtained by $\delta_t=(\alpha_t-\alpha_z)/\alpha_z$ at $t=0°$, 10°, 20°, 30° and 40° in 400 Oe is shown in Table 4.



No.	Ni (%)	Cr (%)	No.	Ni(%)	Cr(%)
1	30.57	7.30	14	33.66	7.99
3	31.86	7.39	16	33.85	9.05
5	31.98	8.50	17	34.02	7.34
7	32.05	5.68	18	34.52	12.22
10	33.06	8.04	19	34.89	10.09
11	33.10	5.89	26	36.12	9.57
12	33.59	8.96			

Fig. 2(a) Permeability-Temperature Curves in 400 Oe for Fe-Ni-Cr Alloys.

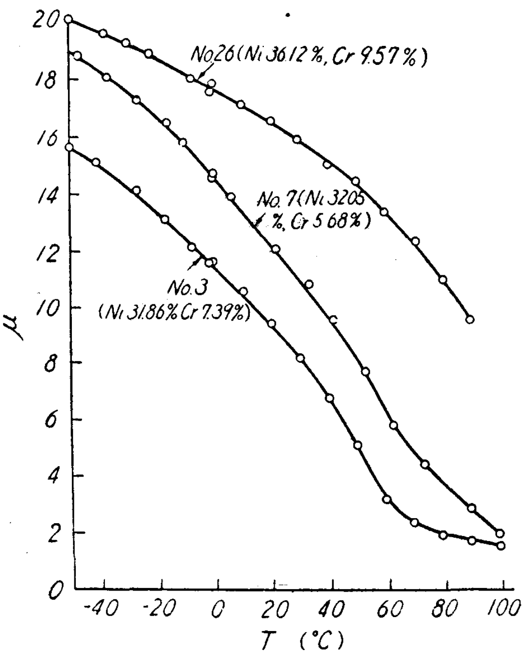


Fig. 2(b) Permeability-Temperature Curves in 400 Oe for Fe-Ni-Cr Alloys.

The above results of the measurements will be briefly considered below in comparison with the standard mentioned in the introduction. In the specimens measured, the magnetic transformation point A_2 is in the range of 0~300°, and the change of the permeabilities due to the temperature is generally remarkable, a considerable number of them being almost linear as is shown in Fig. 2 (a), and this linearity is still maintained even on the side of low temperatures as is shown Fig. 2 (b). Fig. 3 shows the relation between the permeability and its temperature coefficient in 400 Oe at 0° independent on the composition of the specimens. In this figure the area in which the permeability and its temperature coefficient satisfy the standard is bordered with a spuare; to this area belong the specimen numbers, 1, 3, 5, 9, 10, 12, 15, 16 and 20, and round it are situated Nos. 2, 7, 11, 14, 17, 18, 19 etc. comparatively meeting the above requirement. From Table 2 and 3, the specimens having the temperature coefficient which satisfies or nearly satisfies the standard in the temperature range of above 30° are Nos. 1, 3, 5, 7, 10, 11, 12, 14, 16, 17, 18, 19 etc. and plotted on a triangular diagram of Fe-Ni-Cr system as is shown in Fig. 4. In this figure, the numbers with a mark (○) denote those of the specimens and the three curves show the contour lines of transforma-

Table 3. Results of Measurements at Low Temperatures.

Specimen No.	Composition (%)		Field (Oe)	Temperature Coefficient $\alpha \times 10^3$				
	Ni	Cr		α_{-40}	α_{-30}	α_{-20}	α_{-10}	α_z
3	31.86	7.39	300 400 500	5 5 6	6 7 6	7 8 6	8 8 6	8 8 7
7	32.05	5.68	300 400 500	5 4 5	5 5 5	6 6 6	6 7 6	7 7 7
26	36.12	9.57	300 400 500	2 2 2	2 2 2	2 2 2	2 3 2	3 3 3

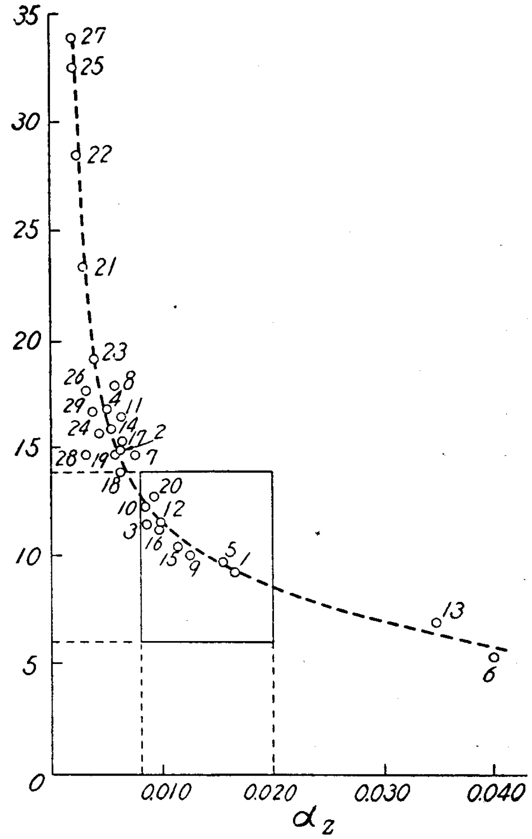
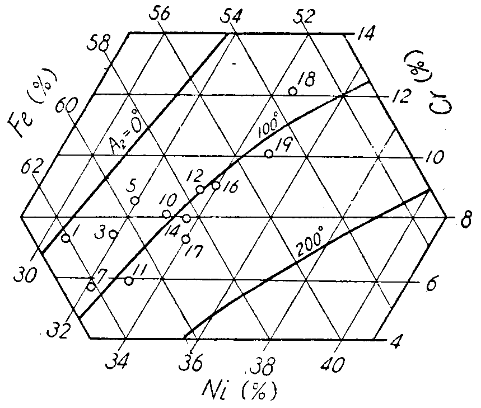


Fig. 3. Relation between Permeability μ_z and its Temperature Coefficient α_z in 400 Oe at 0° for Fe-Ni-Cr Alloys.



No.	μ_z	α_z	No.	μ_z	α_z
1	9.14	0.0166	12	11.54	0.0098
3	11.45	0.0086	14	15.89	0.0054
5	9.65	0.0157	16	11.15	0.0098
7	14.60	0.0077	17	15.30	0.0065
10	12.28	0.0087	18	13.85	0.0063
11	15.45	0.0064	19	14.70	0.0058

Fig. 4. Distribution Diagram of Alloys Showing Excellent Characteristics of Magnetic Shunt for Fe-Ni-Cr Alloys.

tion point A_2(6) of 0°, 100° and 200° respectively. As is seen from this figure, it is noticed that the compositions of specimens satisfying or nearly satisfying the standard lie scattered along the contour line of A_2 of 100°. This means that the magnetic shunt characteristics of these alloy are similar to those of Ni-Cu alloys. It is difficult to draw a contour line of μ_z and α_z in 400 Oe, for the sake of few measurements in Fig. 4. However it can be realized that it has a qualitative trend by the consideration in connection with the contour lines of A_2 of 0°, 100° and 200°. In Fig. 5 is shown the relation between Ni-content and some properties, i. e., permeability μ_z and its temperature coefficient α_z at 0°, mean temperature range $\overline{\Delta T}$ and temperature range ΔT in which the degree of change in α_t to α_z satisfy the standard in 400 Oe. In the figure, the dotted curve is magnetic transformation point A_2. As is seen in the figure, it is clear that the higher the A_2 point, the higher the value of $\overline{\Delta T}$ and ΔT, and the lower the value of α_z. The range satisfying the standard is where A_2 point is below 100°. It seems impossible to obtain from alloys whose transformation point A_2 is above 200° the magnetic shunt materials demanded at present.

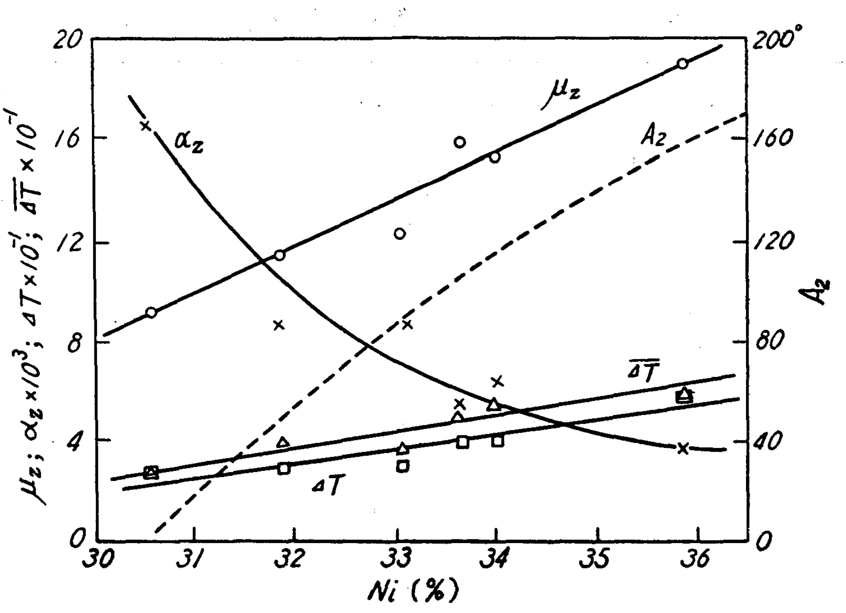
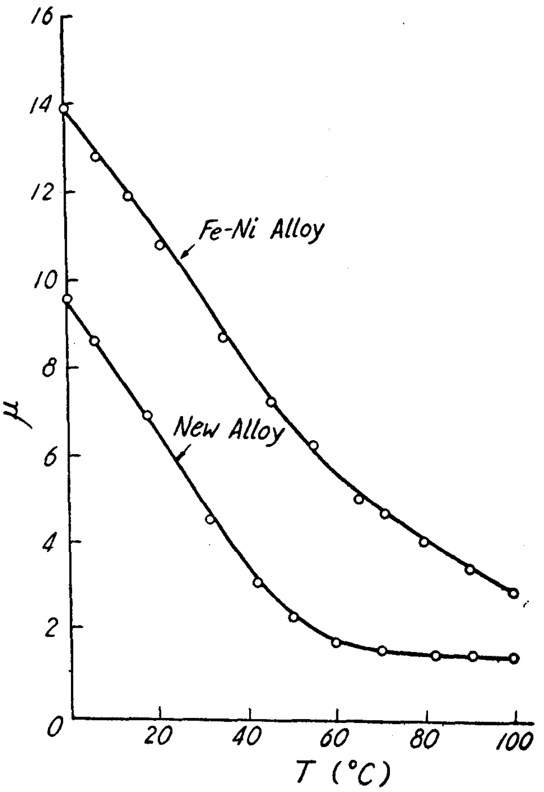


Fig. 5. Relations between Some Properties i. e. μ_z, α_z, ΔT, $\overline{\Delta T}$ and Nickel Contents of Fe-Ni-Cr Alloys Containing Cr≒7.5%.



New Alloy ······ Fe-Ni-Cr Alloy (31.98% Ni, 8.50% Cr, Bal. Fe)
Fe-Ni Alloy······ 30.26%Ni, 0.04%Cr, 0.23 %Mn, 0.04%Si, 0.39%C.

Fig. 6. Permeability-Temperature Curves of New Alloy and Fe-Ni Alloys.

From the results of the above experiments and considerations, we can

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(6) P. Chevenard, Travaux Et Memoires du Bureau International des poids Et Mesures, **17** (1927), 72.

concluded that alloys satisfying the present standard are composed of 30～60% of Ni, 1～18% of Cr and the balance of Fe in Fe-Ni-Cr alloys and have a transformation point in the vicinity of 100° in general, and below 100° in particular. The present writers have designated these alloys "M. S. Alloy" (M. S. is the initials of the capital letters of magnetic shunt).

By way of comparison, is shown in Fig. 6 the permeability-temperature curves in 400 Oe concerning the specimen No. 5 and one of the Fe-Ni magnetic shunt steels now on the market. The Fe-Ni steel is composed of 30.26% of Ni, 0.04% of Cr, 0.23% of Mn, 0.04% of Si and balance of Fe. As is shown in this figure, the M. S. alloy shows a slight decrease on its linearlity above 40° as compored with the Fe-Ni alloy, but the reversibility of its characteristics against the temperature and its reproductivity in manufacture are both extremly excellent.

Summary

The results of the present investigation for the magnetization curves of Fe-Ni-Cr alloys, containing 30～60% Ni and 1～18% Cr, those are melt, forged, cold worked and finally annealed may be summarized as follows:

(1) The relation between the permeability μ_z at 0° and its temperature coefficient α_z is hyperbolic.

(2) As the magnetic transformation point A_2 is raised, the permeability μ_z at 0° increases, while its temperature coefficient decreases.

(3) The higher the temperature of A_2, the larger the temperature range where the temperature coefficient α_t of permeability at each temperature changes linearly.

(4) The alloy satisfying magnetic shunt characteristics, which is widely demanded at present, has a transformation point A_2 of 100° or so.

(5) This alloy containing no C and having no allotropic transformation even at low temperatures is very excellent ones as a magnetic shunt with good reversibility of magnetic properties and reproductivity in manufacture.

In conclusion, the present writers wish to express their cordial thanks to Messrs. Hideji Konno, Tadashi Kikuchi, Taiji Amemiya, Takeshi Miyazaki, for their kind assistance in the present experiment. A part of expenses was defrayed from the Grant in Aid for Fundamental Scientific Research.